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PETROLOGY.

(IGNEOUS ROCKS)

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AN INTRODUCTION TO THE STUDY OF

PETROLOGY:

THE IGNEOUS ROCKS

BY

FREDERICK H. HATCH, PH.D., F.G.S.

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WITH FORTY-THREE ILLUSTRATIONS

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PREFACE.

A LITTLE book that should briefly describe the mineral constituents and internal structures of the Igneous Rocks, their mode of occurrence at the surface and their origin beneath the crust of the earth, has long been a *desideratum* among English text-books of Science.

With the view of filling this gap this little book has been prepared; and it is hoped that it will be found useful, not only as an introduction to the subject, but also as a handy work of reference.

Von Lasaulx's *Einleitung in die Petrographie* served me as a model in the first instance; but in working out my scheme I have thought it desirable to deviate considerably from the arrangement adopted in that excellent little book. In the verification of data Rosenbusch's *Mikroskopische Physiographie* (2 vols.), Fouqué and Lévy's *Minéralogie Micrographique*, Lévy and Lacroix's *Les Minéraux des Roches* and Teall's *British Petrography* have been of great assistance to me; and the illustrations are, in many cases, taken from these works. I have also to thank the Council of the Geological Society and the Editor of the Geological Magazine for permission to reproduce illustrations that have appeared in their journals. The work has profited much by a careful revision of the proof sheets kindly undertaken by Mr. A. Pringle, B.Sc., of the Museum of Practical Geology, London.

Nov. 1890. F. H. H.

28, JERMYN STREET,
LONDON, S. W.

PETROLOGY.

I.

INTRODUCTION.

Petrology is that department of geological science which has for its object the investigation of the characters and relations of rocks, that is to say, of the various materials of which the earth's crust is built up. A **rock** may be defined as a mineral aggregate, possessing a more or less persistent geological character. In studying rocks, therefore, we have three points of departure: (1) their geological relations, or mode of occurrence; (2) their constituent minerals; and (3) the mode of aggregation of the constituent minerals, or rock-structure.

In classifying rocks, we must allow each of these factors its proper value. The exclusive use of one of them would lead to incongruous results. Two rocks, for example, may be composed of the same minerals and yet have originated in totally dissimilar ways, the result being a difference both in structure and in mode of occurrence. Thus, a granite, a felspathic grit and a gneiss may all three be composed of quartz felspar and mica; but in structure and mode of origin they differ widely. The granite, having been produced by the consolidation of a molten magma or paste at some considerable depth beneath the surface, possesses a coarse-grained, highly crystalline structure. The grit, on the other hand, is composed of fragments of minerals, derived from the disintegration of other rocks, that have been transported and deposited by the agency of moving water. While in gneiss there is a banded structure, generally considered to have been produced by a re-arrangement of the minerals since the first formation of the rock.[1]

The three rocks made use of in our example, may be taken as types of the three chief classes into which rocks may be divided; viz., **Igneous**, **Aqueous** and **Metamorphic.**

It is the purpose of the following pages to discuss briefly the characters of the chief Igneous rocks.

---

[1] The banding of some gneisses, however, is possibly an original structure, comparable to "fluxion-structure" in lavas.

II.

MODE OF OCCURRENCE OF THE IGNEOUS ROCKS.

The **Igneous Rocks** are those that have been formed by the consolidation of molten material. We have good reason for believing that the temperature of the interior of the earth is very high—high enough, indeed, to melt all rocks with which we are acquainted at the surface. It is probable, however, that the liquefaction of the igneous masses is held in check by the enormous pressure existing at such great depths. The discussion of this question need not detain us. For, whether the interior of the earth is occupied by rock in the molten condition, or by solid material at a sufficiently high temperature to become liquid under a diminished pressure, the ultimate result is the same: at the moment of eruption the pressure is relieved and the liquid rock injected in the direction of least resistance. According to the nature of the resistance presented by the environment, the molten rock pierces the solid crust of the earth to a greater or less distance; perhaps, ultimately reaching the surface and flowing out in the form of lava, or being reduced by the violence of the explosion to cinders, or even to fine ash.

This consideration leads to a two-fold division of igneous rocks; namely, into those that consolidate at considerable depths beneath the surface, and those that penetrate to upper portions of the crust and are poured out upon the surface. The former are termed **plutonic**, the latter **volcanic** rocks. The different conditions under which plutonic and volcanic rocks consolidate, are the cause of considerable differences in structure. In the one case the gradual consolidation necessitated by the slow rate of cooling, accompanied perhaps by a considerable amount of pressure, produces a highly crystalline and coarse-grained texture; while the rapid hardening of a lava, chilled by being poured out at the surface and spread over a large area of cold rock, and subject only to the pressure of the atmosphere, imparts to it a vitreous character. Granite and rhyolite—rocks of similar chemical and mineralogical composition—illustrate this difference. The granite is wholly crystalline, its large crystals completely filling space to the exclusion of all interstitial matter; while in the rhyolite the crystals are imbedded in a glassy or a devitrified paste, the streaky character of which at once betrays its former viscous condition. Volcanic rocks are connected with their deep-seated or plutonic roots by necks and pipes, or by a ramifying system of dykes and veins. In some cases the superficial strata are pierced by dykes and sheets of igneous material that have found no outlet at the surface. All such igneous masses, penetrating older rocks, are termed **intrusive.** They form the connecting link between plutonic and volcanic rocks.

Mode of Occurrence. The plutonic rocks, being essentially deep-seated, can only appear at the surface in places where there has been much denudation, *i.e.*, where the overlying strata have been removed by erosive agencies (frost, rain, fluviatile and marine action, etc.). They are therefore exposed more frequently in the older than in the younger strata. For this reason granites, syenites, diorites, gabbros and similar plutonic rocks are considered by some geologists to have been formed only in Pre-Tertiary times. That this view is erroneous has been shown in places where the denuding agencies have been sufficiently powerful to expose plutonic rocks of Tertiary age (*e.g.*, in the Western Isles of Scotland).

The shape assumed by an intrusive rock is of necessity regulated by the nature of the passage along which it is injected; or, in the words of Dr. A. Geikie, the shape of the intrusive mass is that of the "channel of escape." On the other hand, volcanic rocks erupted at the surface appear in beds or streams.

The following terms are used in describing the chief forms in which igneous rocks occur :—

Boss.—Any irregularly shaped mass. The plutonic rocks—granite, syenite, diorite and gabbro—occur usually in this form.

Laccolite.—A dome-shaped mass, produced by the intrusion of molten rock between two beds, where, having a limited lateral extension, it has *elevated* the overlying strata. This is one of the commonest forms in which igneous rocks occur. The out-crop produced by it is an "elongated oval, or lenticular patch, having the long axis in the direction of strike of the neighbouring strata."[1]

Intrusive Sheet, or **Sill.**—A flat bed of rock produced by the uniform intrusion of molten material between the planes of stratification. Such sheets are liable to be mistaken for contemporaneous lava-flows; from which, however, they may be distinguished by the following points of difference: (1) they break across the bedding, appearing here on one horizon, there on another; (2) they sometimes send off veins into the strata above them, as well as into those below them; (3) they alter the beds both above and below them; (4) they are rarely vesicular or amygdaloidal; (5) they are not accompanied by tuffs. Dolerites and diabases frequently occur in intrusive sheets.

Dykes and **Veins.**—A dyke is a wall-like mass of igneous rock, produced by the injection of molten material into a vertical or highly inclined crack. Veins are produced by the infilling of smaller and less regular cracks. Dykes sometimes form marked features in the scenery of a district; for, being more capable of resisting the weather than the rocks they traverse, they remain standing, like huge walls, when the softer rocks have been worn away. Occasionally, however, they weather more rapidly, and then produce troughs. Elvans, greenstones, mica-traps, basalts, etc., occur as dykes.

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[1] Harker: "The Bala Volcanic Series," 1889, p. 43.

Necks.—Necks are the filled-up channels or pipes by which the erupted material made its escape. Usually they are plugs of consolidated igneous rock, surrounded by beds of volcanic ejectamenta. Sometimes, however, they consist entirely of fragmentary material produced by the violence of the explosions that precede or accompany an eruption.

Lava-flows.—Lavas are produced by the consolidation of molten rock, as it flows out from the volcanic vent. They form beds or streams of greater or less extent, according to the fluidity of the erupted material, the more basic magmas being the more fluid. They often present marked flow-structures (ropy and stringy surfaces, internal streakiness, etc.), due to the rolling over and pulling out of the plastic semi-solid mass. They are often also cellular, vesicular, slaggy, or vitreous.

When the flows take place in an area of deposition, *e g.*, on a sea-bottom, the lava-beds lie upon and are covered by sedimentary rocks of practically the same age as themselves. In such cases they are said to be **contemporaneous** with the strata with which they are interbedded. Submarine eruptions have taken place since the earliest Palæozoic times, so that contemporaneous igneous rocks occur in formations of various ages.

Volcanic Ash-beds, or **Tuffs.**—When the eruption is accompanied by explosion, the molten rock is ejected in the form of bombs, cinders (*lapilli*), and fine ash, which are deposited in layers. The consolidation of this material produces volcanic breccias, tuffs, etc. (Fig. 1). The fragmentary material ejected from volcanoes often becomes mixed with the ordinary sediment on the sea bottom, causing the formation of "ashy beds."

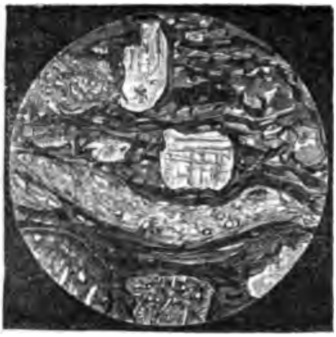

FIG. 1.

III.

THE CONSTITUENT MINERALS OF THE IGNEOUS ROCKS.

THE rock-forming minerals may be variously classified according to the part played by them in the structure and composition of rocks. A useful division is into original and secondary. **Original** minerals are those that came into existence with the rock of which they form part, or that existed before it. They are **secondary** when they are the result of the alteration or reconstruction of the original minerals (by weathering, contact and dynamic metamorphism, etc.).

Original minerals may be further divided into essential and accessory. An **essential** mineral is one whose presence is implied by the name of the rock. An **accessory** mineral is one whose presence or absence does not affect the name of the rock. Thus, quartz, felspar and mica are essential constituents of granite; while zircon, sphene and apatite are accessory.

Another division is into authigenic and allogenic An **authigenic** mineral is one that came into existence with or after the rock containing it. An **allogenic** mineral is one that is of more ancient origin than the rock containing it.

The chief minerals occurring in Igneous rocks are the following:

1. ORIGINAL.

(*a*) *Essential.*

Quartz. Felspars. Nepheline and Leucite minerals. Muscovite.	Colourless.[1]
Biótite. Amphiboles. Pyroxenes. Olivine.	Coloured ferro-magnesian silicates.

(*b*) *Accessory.*

Haüyne and Nosean. Scapolite. Melilite. Sodalite. Apatite. Zircon.	Colourless, or slightly coloured.
Spinels. Garnets. Tourmaline. Sphene.	Coloured.
Magnetite. Ilmenite. Pyrites.	Opaque.

---

[1] This arrangement according to colour (under the microscope) must not be taken too strictly: minerals, which when pure are colourless, are sometimes coloured by the presence of a small quantity of some foreign body.

2. SECONDARY.

Quartz, Opal, Chalcedony. Calcite. Zeolites. Kaolinite. Talc. Muscovite. Zoisite.	Colourless.
Epidote. Leucoxene (Sphene). Chlorite. Serpentine. Uralite (Hornblende).	Coloured.

(*a*) *In Slates and Shales.*

Andalusite.
Chiastolite.
Sillimanite.
Staurolite.
Tourmaline.
Mica, etc.

(*b*) *In Limestones.*

Idocrase (Vesuvianite).
Dipyre (Couseranite).
Wollastonite.
Diopside.
Salite, Malacolite, Diopside (Augites).
Mica.

With regard to the appearance of the rock-forming minerals in thin sections under the microscope, we must take into consideration variations in (1) External contour or form, (2) Internal micro-structure.[1]

1. External Contour or Form.—If the conditions that prevailed during the consolidation of the rock, have been such as to allow of the free growth of crystals, the minerals are bounded on all sides by crystallographic contours, and are said to be **idiomorphic.** If, on the other hand, the minerals have had to struggle for existence, so to speak, they will have naturally hindered one another in their crystallographic development, and the result is an aggregate of grains bounded by **allotriomorphic** contours. Sometimes a mineral which doubtless originally possessed crystallographic form, owes its present irregular fretted outline to the corrosive action of the molten magma in which it floated prior to solidification. A dark zone[2] often surrounds corroded ferro-magnesian minerals, especially the hornblende and mica of andesites and basalts. Incipient or abortive forms (crystallites, microlites, skeleton-crystals, etc.) frequently occur in vitreous rocks where the solidification has been too rapid to permit of full crystallographic development (see p. 69).

The index of refraction of a mineral also influences its outline as seen under the microscope.

2. Internal Micro-structure.—The principal variations in micro-structure are produced by cleavage, inclusions and alteration.

---

[1] Optical phenomena cannot be gone into in a work of these dimensions. The student should consult *Notes on a new Form of Polarizing Microscope*, by Mr. A.B.Dick, published by Messrs. Swift & Sons, 81, Tottenham Court Road, W.

[2] "Zone of corrosion," *Ger.* = Einschmelzungszone.

Cleavage shows itself, in thin sections, in lines of greater or less distinctness, sharpness and regularity, according to its degree of perfection. A perfect cleavage gives numerous very fine straight lines, while an imperfect one gives thick branching and irregular lines. The relative position of cleavage lines depends on the direction of the section through the mineral. A prismatic cleavage produces, as a rule, two sets of parallel lines, while a basal or pinacoidal cleavage furnishes only one set.

Inclusions. — During their formation, crystals take up and inclose portions of the matrix from which they have separated and other foreign bodies. These inclusions may bear a definite crystallographic relation in their arrangement to the shape of the crystal (*i.e.*, they may be *central, peripheral, or zonal*), or they may be distributed indefinitely. They are of three kinds :— (1) gaseous, (2) liquid, (3) glassy and (4) mineral. **Gas-inclusions** are small, round, or elliptical pores filled with air or carbon dioxide. Occasionally they have the inverse shape of their host, being, in fact, negative crystals. In consequence of the difference in refractive index between the gas and the mineral substance inclosing it, gas-inclusions are always bounded by a well-marked dark border. **Liquid-inclusions** are also round, elliptical, or tubular bodies, having a contour somewhat less strongly marked than that of gas-inclusions. The liquid, which may consist of water or carbon dioxide, liquid under pressure, usually does not quite fill the cavity, and a small movable bubble remains. When sufficiently small, the bubble possesses a constant vibratile motion. The water is sometimes saturated with common salt, and may then contain cubic crystals of that mineral. Liquid-inclusions occur abundantly in many minerals, notably in quartz (see Fig. 2). **Glass-inclusions** are distinguished from liquid-inclusions, by the sharpness of their contours and the fixity of their bubble. Also more than one bubble is frequently present. The inclosed glassy substance is often coloured or turbid, especially when such is the case with the glassy base of the rock (see Fig. 3). Devitrification, or the development of crystallites and microlites, may also have taken place (see Fig. 4). **Mineral-inclusions** are distinguished from the foregoing by the possession of idiomorphic contours.

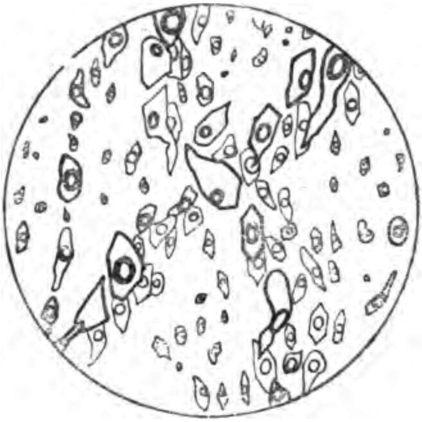

FIG. 2.
Liquid Inclusions in Quartz.
(After Fouqué and Lévy.)

They may consist of needles, rods, granules, plates or scales, and are often arranged along planes bearing a definite relation to the symmetry of the crystal in which they are included, being then often the cause of the optical phenomena known as *schiller*, *chatoyancy* and *asterism*.

The **alteration** of minerals is due either to chemical changes brought about by percolating thermal waters, weathering, etc., or to mechanical stress. But the two often operate simultaneously. Chemical change may consist in the alteration of one mineral to another, by taking up water, etc. (as in the alteration of olivine into serpentine), or in the breaking up of a complex body into a number of simpler ones, as in the formation of saussurite (an aggregate of

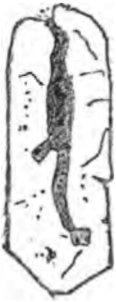

FIG. 3.

Crystal of Augite, containing a vitreous core. (*After Hatch.*)

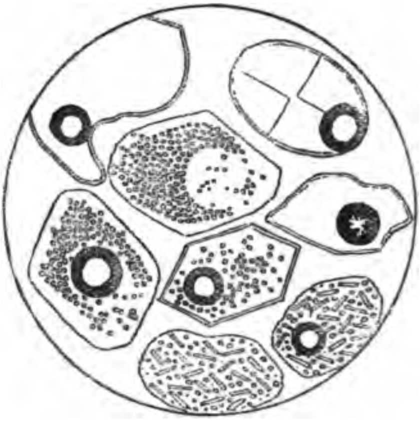

FIG. 4.

Glass Inclusions with bubbles and crystallites. (*After Fouqué and Lévy.*)

epidote, zoisite, albite, etc.) from plagioclase felspar. Mechanical alteration comprises granulation, linear extension and paramorphic change (augite to hornblende, etc.). See *Alteration of Rocks* (p. 75).

SILICA GROUP.

Quartz. Pure silica, SiO_2. Crystallizes in the rhombohedral system, the crystals being usually bounded by the hexagonal prism (recognisable by its horizontal striations) with pyramidal (rhombohedral) terminations. Sometimes, however, the prism faces are absent, the crystals then consisting of the double pyramid of twelve faces. Unattacked by acids, excepting hydrofluoric acid. Insoluble in potash (distinction from opaline silica). Sp.G. = 2·6. Hardness = 7.[1]

Quartz is the mineral eminently characteristic of the acid rocks. In granite and quartz-diorite, it occurs in irregular grains without definite crystalline contours; and in microgranites, felsites and rhyolites, in rudely contoured, often bipyramidal crystals, generally much corroded by the surrounding magma. As a secondary constituent quartz fills cracks, joints and cavities (*vein-quartz*); similarly it occurs in association with felspar, mica, tourmaline, etc., in the so-called pegmatite-veins.

Quartz may be recognised by its hardness, pellucidity and vitreous lustre. Usually it is colourless, sometimes, however, brownish or yellowish (*smoky*

---

[1] Moh's Scale, viz., 1 = talc; 2 = gypsum; 3 = calcite; 4=fluorspar, 5=apatite, 6=orthoclase, 7=quartz, 8=topaz, 9=corundum, 10=diamond.

quartz, cairngorm, etc.), pink (*rose quartz*), or bluish (in certain gneisses and Palæozoic grits). Under the microscope it appears in colourless grains, characterized by the presence of innumerable minute liquid inclusions generally arranged along lines and planes. High magnification discloses in many of these a minute vibratile bubble, occasionally also cubes of salt, showing that the liquid, in some cases at least, consists of a saturated solution of that mineral. In other cases, the inclosed substance has been proved to be carbon dioxide. Between crossed nicols the polarization-colours[1] vary, in moderately thin sections, between a light grey and pale yellow of the first order of Newton's scale of colours. Thicker sections, of course, show brighter colours (yellow, blue, red, etc.). Sections perpendicular to the vertical (here coincident with the optic axis) give a uniaxial interference-figure.[2]

Tridymite. Pure silica, SiO_2. Triclinic, but affecting hexagonal symmetry. In thin six-sided colourless tablets, which split up between crossed nicols into a number of depolarizing areas, showing light and dark banding. Insoluble in acids; soluble in alkalies. Sp. G. = 2·3. Hardness = 7. Tridymite occurs in volcanic rocks (rhyolites, trachytes and andesites), generally in cavities in pretty groups of interpenetrating twins and trins. Under the microscope it is described as occurring in imbricated aggregates.

---

[1] All doubly refractive minerals are coloured between crossed nicols, the degree of coloration depending on the amount of separation of the two rays for any particular mineral and on the thickness of the section.

[2] A black cross, which in thick sections is surrounded by concentric coloured rings.

Opal, Hyalite. Hydrated silica: $SiO_2 + xAq$. This mineral occurs in amorphous masses resulting from the solidification of colloid or hydrated silica. Colour variable: yellow, brown, etc. Translucent to opaque. Soluble in alkalies (distinction from quartz) Sp.G. = 2·2.

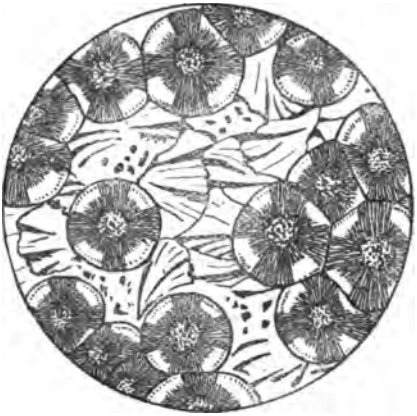

FIG. 5.

Spherulitic Opal in a chalcedonic matrix, between crossed nicols. (*After Fouqué and Lévy.*)

Opal is a secondary constituent of many acid volcanic rocks (rhyolites, trachytes and even the less acid andesites). It is also deposited from the water of hot springs and geysers (*geyserite*). Hyalite, a pure colourless variety, frequently occurs in andesites.

Under the microscope it is isotropic, but occasionally shows weak double refraction and gives a black cross between crossed nicols (spherulitic opal, see Fig. 5).

Chalcedony. Silica, SiO_2. Mixtures of crystalline and amorphous silica. Cream-coloured to colourless; translucent to semi-opaque. Insoluble in acids; partially soluble in alkalies. Sp. G. = 2·59 – 2·64.

A secondary constituent of acid volcanic rocks. Under the microscope chalcedony has a fibrous structure, giving an imperfect black cross between crossed nicols (see Fig. 5.)

Agate consists of alternating layers of chalcedony, jasper, amethyst and other varieties of quartz. It is found wholly or partially filling the amygdaloidal cavities of old vesicular lavas (melaphyre, basalt, etc.).

FELSPAR GROUP.

The felspars crystallize in two systems, the monoclinic and the triclinic; but the forms of the two systems are very similar, and the angles differ by a few degrees only.

The chief *monoclinic felspars* are orthoclase and sanidine. *Triclinic* are albite, oligoclase, andesine, labradorite and anorthite; they are comprised under the general term *plagioclase.*

The commonest combination of faces presented by the felspars consists of the following forms: the basal plane (generally denoted by P), the clino- or the brachy-pinacoid (M), the prisms (T and l), the two ortho- or the two macro- domes (x and y), the clino- or the brachy-dome (n), and the pyramid (o), (Fig. 6).

The principal cleavage is basal (P); but this is nearly equalled by the cleavage parallel to M. These two cleavage planes are at right angles in orthoclase, but are inclined to one another in plagioclase. Under the microscope orthoclase presents sections that are uniformly affected by polarized light, or are divided into two areas that present uniform polarization respectively (dual twinning on the Carlsbad type); whereas plagioclase usually has a striated appearance between crossed nicols, due to the fact that the triclinic felspars are subject to repeated ("polysynthetic") twinning on the Albite type.

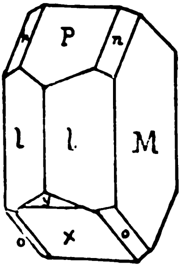

FIG. 6.

Crystal of Orthoclase.
P. Basal plane.
M. Clinopinacoid.
l. Prism.
x and *y*. Orthodomes.
o. Pyramid.
n. A Clinodome.
(*After Rosenbusch.*)

Considered chemically, the felspars are silicates of alumina and one or more of the bases potash, soda and lime. There are three primary felspar substances: potash-felspar (K_2O, Al_2O_3, $6SiO_2$), soda-felspar (Na_2O, Al_2O_3, $6SiO_2$), and lime-felspar (CaO, Al_2O_3, $2SiO_2$). They occur in nature as orthoclase, albite and anorthite respectively. By their combination in definite proportions two important series of felspars are formed: a *lime-soda* series, comprising the well-known members, oligoclase, andesine and labradorite, to which may be added further, bytownite; and a *potash-soda* series, which has not yet been thoroughly investigated.

The *potash-soda* series is only represented by the isolated occurrence of felspars that have been variously described as soda-orthoclase, soda-microcline, and anorthoclase. The crystals have an unusual form, due to the predominance of the prisms (*T* and *l*) and the orthodome (*y*). Like microcline, anorthoclase is generally referred to the triclinic system: between crossed nicols, intersecting systems of extremely fine twin-lamellæ are generally recognisable. It has been described as occurring in the *Rhombenporphyr* of Southern Norway, in the trachytes of Pantellaria and in the keratophyres of the Hartz.

1. MONOCLINIC FELSPARS.

Orthoclase, or potash felspar. Chem. comp. = K_2O, Al_2O_3, $6SiO_2$ (65% SiO_2, 17% K_2O and 18% Al_2O_3). Sp. G. = 2·54 – 2·57. Hardness = 6. Unattacked by acids except hydrofluoric acid. Two types of crystal are common:—flat tables (with *M* largely developed) and stout prisms. A roof-like termination is produced by the basal plane (*P*) and the orthodome (*x*), which are about equally inclined to the vertical axis, and form with one another an angle of 129° 43′. (See Fig. 6.) The crystals present dual twinning on various types (Carlsbad, Manebach, Baveno, etc.), the commonest being the Carlsbad.

When twinned on this type, the crystals are usually united on the clino-pinacoid (*M*), the basal planes (*P*) of the crystals being inclined in opposite directions. (See Fig. 7.) Twinning of this nature is often revealed in thin sections by the difference in extinction shown by the two halves when rotated between crossed nicols.

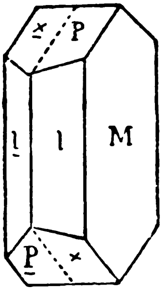

FIG. 7.
Orthoclase Crystal twinned on the Carlsbad-type.
P. Basal plane.
M. Clinopinacoid.
l. Prism.
x. An Orthodome.
(*After Rosenbusch.*)

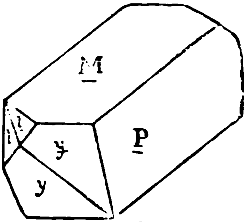

FIG. 8.
Crystal of Orthoclase twinned on the Baveno-type.
P. Basal plane.
M. Clinopinacoid.
l. Prism.
y. An Orthodome.
(*After Rosenbusch.*)

Orthoclase occurs pure and colourless in the variety termed **adularia.** Usually, however, it is turbid and cloudy, due to the development of various decomposition products (kaolinite, muscovite, talc). Between crossed nicols sections of ordinary thinness polarize in grey tints, the double refraction being considerably less than in quartz.

Orthoclase occurs as an essential constituent of the more acid plutonic and older volcanic rocks (granite, syenite, felsite), often in large well-developed crystals (granite-porphyry, felspar-porphyry). Also in foliated rocks (gneiss and various schists); and, together with quartz and other minerals, in segregation veins (pegmatites). Among the sedimentary rocks it occurs in the so-called felspathic grits or arkoses, which are derived from the disintegration of granite rocks.

Sanidine is the name given to a clear, glassy, fissured variety of orthoclase occurring in the more recent acid lavas (rhyolite, trachyte, obsidian). It usually occurs in flat tables, twinned on the Carlsbad type; also in prismatic crystals and irregular grains. Under the microscope it differs from orthoclase in its pellucidity. Inclusions (glass, etc.) are, however, common. The crystals have often undergone fracturing and corrosion during the eruption of the lava in which they were suspended.

2. TRICLINIC FELSPARS.

Plagioclase or lime and soda felspars. In crystal form, similar to orthoclase, with the difference that the basal plane (*P*) instead of being normal to the brachypinacoid (M) is inclined to it (from left to right) at an angle of 86°–87°. The distinguishing character of the triclinic felspars is the lamellar or polysynthetic twinning. The fine lineations produced by this type of twinning can be easily seen with the pocket lens on the faces of the basal cleavage. In thin section, between crossed nicols, it appears as a parallel striation, consisting of light and dark bands, due to the simultaneous extinction of alternate lamellæ. Usually the striation is parallel to the brachypinacoid (M): this constitutes the *albite type* of twinning. (See Figs. 9 and 10.) A second series of twin-lamellæ sometimes cross these at right angles, constituting the *pericline type* of twinning.

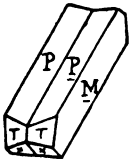

FIG. 9.
Crystal of Plagioclase twinned on the Albite-type.
P. Basal plane.
M. Brachypinacoid.
T. Prism.
x. A Macrodome.
(*After Rosenbusch.*)

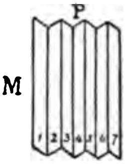

FIG. 10.
Repeated twinning on the Albite-type
P. Basal plane.
M. Brachypinacoid.
(*After Rosenbusch.*)

The researches of Tschermak have shown that the members of the lime-soda series may be regarded as isomorphous mixtures of albite and anorthite in varying proportions. They form a graduated series both with regard to their chemical constitution and their optical and other physical properties (specific gravity, etc.). It is convenient to make use of the names oligoclase, andesine, and labradorite, to fix certain points in the series. If we represent the soda-felspar molecule ($Na_2O.\ Al_2O_3.\ 6SiO_2$) by Ab and the lime-felspar molecule ($2\ CaO.\ 2Al_2O_3.\ 4SiO_2$) by An., then the intermediate felspars have the composition represented by the following average formulæ[1]:—

	Formulæ.	Sp. G.
Albite	Ab	2·62
Oligoclase	$Ab_{10}An_3$	2·65
Andesine	Ab_2An_1	2·67
Labradorite	Ab_2An_3	2·70
Anorthite	An	2·75

With regard to the optical properties of plagioclase, the extinction-angles are smaller for the soda end of the series (albite, oligoclase and andesine) than for the lime end (labradorite and anorthite). In general, a high extinction-angle may be taken as indicating a felspar of the basic (or lime) end of the series; while a low extinction-angle indicates a felspar of the albite, oligoclase, or andesine type. Microlites consisting of a felspar intermediate in composition between oligoclase and andesine, extinguish straight.

The plagioclase felspars usually contain numerous inclusions :—liquid, glass and mineral matter (hæmatite, rutile, mica, etc.). These may be irregularly distributed or arranged along certain crystallographic planes, or in zones parallel to the periphery of the crystal.

The following minerals result from the decomposition of plagioclase:—epidote and zoisite (in the so-called saussurite) and calcite.

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[1] Lévy and Lacroix.

Albite, oligoclase and andesine, are not attacked by hydrochloric acid; labradorite is a little, while anorthite is decomposed with separation of gelatinous silica. The fusibility is greatest in albite and decreases with the diminution of soda and the increase of lime. The specific gravity, on the other hand, is least at the soda end and greatest at the lime end (see table given above).

Just as orthoclase is characteristic of the acid rocks, so the different plagioclase felspars are found in rocks of intermediate and basic composition. Oligoclase and andesine occur in the porphyrites and andesites; labradorite and anorthite in diorites, gabbros, dolerites and basalts. Oligoclase accompanies orthoclase in many granites and trachytes. Albite is frequently present as a secondary constituent ("secondary felspar") in the so-called felspar-quartz mosaic of mechanically metamorphosed rocks. It occurs in these in clear unstriated granules, scarcely distinguishable from quartz but for the fact that they give a *biaxial* interference-figure in convergent polarized light.

Microcline is a triclinic potash felspar, very nearly allied in composition and external form to orthoclase. It is distinguishable from that mineral, however, by a characteristic cross-hatching that becomes visible when the mineral is viewed between crossed nicols. This structure is generally ascribed to intersecting systems of twin-lamellæ (on the albite and pericline types); it differs, however, from ordinary cross-twinning in the fact that in a microcline the lamellæ appear spindle-shaped, instead of being bounded by parallel edges.

Perthite. Both orthoclase and microcline are often intergrown with triclinic felspar (albite or oligoclase), the plagioclase occurring in narrow lamellæ intercalated along planes parallel to the orthopinacoid. In sections parallel to the basal plane or clinopinacoid the included felspar appears in patches and strips which are distinguishable from the main mass of the orthoclase by their twin-striation or by their different extinction-angle. Such admixtures are known as perthite or micro-perthite.

NEPHELINE-LEUCITE GROUP.[1]

Nepheline. Silicate of potash, soda and alumina: $(NaK)_2O, Al_2O_3, 2SiO_2$. Crystallizes in the hexagonal system. It occurs in small colourless and glassy six-sided prisms (combination of hexagonal prism and basal plane).

Soluble in hydrochloric acid with separation of gelatinous silica; the solution gives cubes of salt when evaporated. Sp. G. = 2·6; hardness = 5·5 – 6. Nepheline is essentially a volcanic mineral, being found principally in the cavities of ejected blocks (Monte Somma, Lake Laach). It also occurs as an essential constituent of certain lavas (phonolite, nepheline-basalt, tephrite, etc.)

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[1] Also called FELSPATHOID GROUP, on account of the resemblance of these minerals to the felspars.

Under the microscope it gives hexagonal and four-sided sections; but occurs more frequently in small granules the presence of which can often only be demonstrated by treatment with hydrochloric acid and subsequent staining with fuchsine. The four-sided sections extinguish straight between crossed nicols; while the six-sided ones give a uniaxial interference figure in convergent light. The double refraction is weak, the polarization colour never exceeding a grey tint.

This mineral is peculiarly subject to alteration, usually to zeolitic products, the most frequent being natrolite in fibrous bundles.

Nepheline is liable to be confused with apatite. The latter mineral, however, occurs usually in longer needles than nepheline. Chemically they may be distinguished by the phosphate-test for apatite, and by gelatinization and staining with fuchsine for nepheline.

Elæolite is a dull grey or greenish variety of nepheline occurring in the more ancient crystalline rocks (elæolite-syenite). It forms irregular masses of considerable size, somewhat resembling quartz, from which it may be distinguished by its characteristic greasy lustre.

Elæolite bears the same relation to nepheline that orthoclase does to sanidine.

Leucite. Silicate of alumina and potash: K_2O, Al_2O_3, $4\ Si\ O_2$.

Tetragonal, but in symmetrical combinations, closely resembling the icositetrahedron of the Regular System. Colour, dirty white or grey. Attacked slowly by hydrochloric acid with separation of pulverulent silica. Sp. G. = 2·45 – 2·5. Hardness = 5·5 – 6. Fusible with difficulty.

Leucite occurs almost exclusively as a constituent of the more recent volcanic rocks:—leucitophyre, leucito-tephrite and leucitite.

Under the microscope it presents colourless polyhedral (usually eight-sided) sections. The double refraction is weak, a pale-grey light being transmitted between crossed nicols. The larger individuals present intersecting systems of alternately light and dark twin-lamellæ. Peripheral zones of inclusions (glass, magnetite, etc.) are common.

Melilite (Humboldtilite). Silicate of alumina, iron, lime, magnesia and soda: $12(CaMg)O, 2(AlFe)_2O_3, 9SiO_2$. Tetragonal, occurring in small square tablets and prisms, also in irregular grains. Colour, white to yellow. Gelatinizes easily with hydrochloric acid. Sp. G. = 2·90 – 2·95. Hardness = 5 – 5·5.

Occurs as a constituent of certain basalts (melilite-basalt) and nepheline and leucite rocks.

Under the microscope it appears in colourless grains, which are characterized by a striation normal to the long axis (*peg-structure*).

MICA GROUP.

The rock-forming micas may be divided for all practical purposes into white and dark micas.

In white mica (muscovite), there is usually a considerable divergence of the optic axes; while the dark mica (biotite) is, in most cases, practically uniaxial, *i.e.*, the two optic axes are nearly coincident. There are, however, certain rare varieties of mica that have a large optic axial angle. Both micas are monoclinic, but with pseudo-hexagonal symmetry (see Fig. 11);

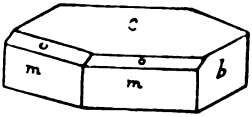

FIG. 11.
Crystal of Mica.
c. Basal plane.
o. Pyramid.
m. Prism.
b. Clinopinacoid.
(*After Rosenbusch*)

and a very perfect basal cleavage is characteristic for both. The elasticity of the laminæ distinguishes mica from other minerals (talc, chlorite, etc.) possessing a similar cleavage.

White Micas.

Muscovite, or Potash-mica. Hydrated silicate of alumina and potash: $K_2O,3Al_2O_3,6SiO_2, 2H_2O$ (Tschermak).

Not attacked by hydrochloric acid. Sp. G. = 2·76 – 3·1. Hardness 2 – 3.

Occurs in plates, leaves, scales and fibres, possessing a silvery white colour and bright lustre, in granite and gneiss. Fragments of muscovite are frequently present in sandstones and shales, and by their parallel arrangement impart to these rocks a fissile character. Under the name of **sericite** a silvery white or pale green variety occurs as a frequent secondary constituent of the metamorphic schists. There is no doubt that in many cases it results from the alteration of the felspar. Its thin laminæ wrap round the lenticular masses of quartz and felspar, and play an important part in determining the schistosity of these rocks.

Other white micas are **paragonite**, a hydrated silicate of alumina, potash and soda, occurring in schists; **margarite**, a hydrated silicate of alumina and lime, in schists; and **lepidolite** and **zinnwaldite**, hydrated silicates of alumina, potash, soda and lithia, in pegmatites. Under the microscope the white micas give lath-shaped sections, presenting well-marked cleavage-lines, often bent. They also occur in streaky and ribbon-like bands. Between crossed nicols, brilliant chromatic polarization.

BLACK OR FERRO-MAGNESIAN MICAS.

Biotite (*Meroxene* and *Lepidomelane*), a hydrated silicate of alumina, iron, magnesia and potash. Attacked by hot hydrochloric acid. Sp. G. = 2·8 – 3·2. Hardness = 2·5 – 3.

Occurs as an essential constituent of granite and granitite, mica-trap, trachyte and andesite; also, as an accessory in some basalts. Loose crystals are found embedded in volcanic ash.

Developed also in diabase by contact with granite.

Under the microscope this mineral appears in plates, scales and lath-shaped sections, the latter showing intense pleochroism (pale-yellow to chestnut-brown and black). The principal absorption takes place when the long axis of the lamella is parallel to the short diagonal of the polarizing nicol, thus distinguishing it from tourmaline, which is equally strongly absorptive, but in the reverse direction.

Inclusions are frequent:—tourmaline, zircon, allanite, sphene and apatite, the last four of which are often surrounded by pleochroic borders.

Alters easily to chlorite, the alteration being marked by the gradual assumption of a green colour.

Other dark micas are **anomite** and **phlogopite,** occurring in volcanic and metamorphic rocks. They are of the same general chemical composition, but differ in optical properties.

AMPHIBOLE GROUP.

The amphiboles are silicates mainly of magnesia and lime, in which the magnesia predominates over the lime; other bases occurring in some varieties are alumina, iron, manganese and soda. They are nearly all monoclinic, only one variety being rhombic (anthophyllite) and one triclinic (cossyrite). (See Fig. 12.)

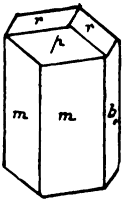

FIG. 12.

Crystal of Hornblende.

p. Basal plane. | m. Prism.
r. Pyramid. | b. Clinopinacoid.

(*After Rosenbusch*).

Sp. G. = 2·90 – 3·55. Hardness = 5 – 6. Unattacked by acids. Cleavage, parallel to the prism (angle = 124°), well-marked. (See Fig. 13.)

Under the microscope, sections perpendicular to the vertical axis are generally six-sided (being bounded by two clinopinacoidal and four prismatic planes) with cleavage-lines intersecting at an angle of 124° (see Fig. 13). They frequently show dual, more rarely multiple, twinning. Between crossed nicols, the extinction-angle, measured to the vertical axis, varies from 0° to a maximum of 22° (in augite, the maximum often reaches 45°). The double refraction is high, even thin sections giving chromatic polarization. The coloured varieties are strongly pleochroic (distinction from augite).

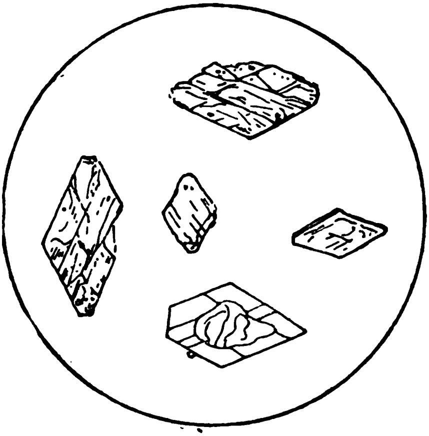

FIG. 13.

Crystals of Hornblende, under the microscope, showing the predominance of the prism faces over those of the pinacoid, and the prismatic cleavage. (*After Teall.*)

By alteration processes (weathering, metamorphism, etc.) the amphiboles give rise to chlorite, serpentine and calcite.

1. Monoclinic Amphiboles.

a. Brown and Green Amphiboles.

Common Hornblende. Monoclinic. Silicate of iron, alumina, lime and magnesia; rich in alumina and iron. Colour, brown or green. Pleochroism, strong in brown and yellow, or green and yellow tints ($\gamma \geqq \beta > \alpha$).

Occurs in hornblende-granitite and syenite (brown and green varieties), diorite (mainly the green variety), trachyte (usually green variety), and andesite (brown variety), and as an accessory constituent of basalt. The crystals are among the first-formed constituents, and have often suffered subsequent corrosion in the still molten magma, being then surrounded by a dark-coloured border.

b. Green Amphibole.

Actinolite. Monoclinic. Silicate of iron, magnesia and lime: $3CaO,(Mg\ Fe)O,4SiO_2$. Colour, grass-green. Pleochroism, in green tints, not very strong. Maximum extinction-angle = 18°. Occurs in long prisms and needles, or in ribbon-like blades and fibres, as a constituent of amphibolite and hornblende-schist.

Smaragdite, nephrite and **uralite** are fibrous green hornblendes, generally secondary after augite. Such paramorphic hornblende occurs in gabbros, diabases and epidiorites.

c. White Amphibole.

Tremolite. Monoclinic. Silicate of magnesia and lime: $CaO, 3MgO, 4SiO_2$.

Non-pleochroic, because colourless. Maximum extinction = 18°. Occurs in lamellar and bladed aggregates as a constituent of metamorphic limestones (cipolines).

Asbestus is a fibrous variety, used for making fire-proof cloth, etc.

d. Soda-Amphiboles.

Arfvedsonite. Monoclinic. Silicate of soda and iron—$Na_2O,Fe_2O_3,4SiO_2$.

Resembles common green hornblende. Maximum extinction-angle varies from 0° – 12°. Occurs in association with the soda-minerals—elæolite, nepheline and leucite—in elæolite-syenite, phonolite, etc.

Glaucophane. Monoclinic. Silicate of alumina and soda—$Na_2O, Al_2O_3, 4SiO_2$. Colour, blue. Pleochroism striking, in blue and reddish violet tints, (γ = blue, β = reddish violet, a = colourless to yellow). Maximum extinction-angle = 5°. Occurs in prisms and blades in glaucophane-schist (Anglesey, Isle of Syra, Japan). **Gastaldite** is a variety.

Riebeckite. Monoclinic. Silicate of soda and iron—$Na_2O,Fe_2O_3,4SiO_2$. Colour, deep blue. Pleochroism in blue and green tints, (γ = green, β = blue, a = deep blue). Maximum extinction = 5° – 7°. Occurs in certain felsites (Socotra, Myndd Mawr in Wales, Ailsa Craig in Scotland). **Crocidolite** is a variety.

2. RHOMBIC AMPHIBOLE.

Anthophyllite. Rhombic. Silicate of magnesia and iron—$(MgFe)O,SiO_2$. Colourless. Extinction straight. Occurs in bladed forms in amphibolites. Also in fibrous zones around the olivines of some gabbros.

3. Triclinic Amphibole.

Cossyrite. Triclinic. Silicate of alumina, iron and soda. Under the microscope this mineral appears in prisms of a deep reddish-brown colour, only transmitting light in very thin sections.

It is only known to occur in the rhyolites of Pantellaria (pantellerites).

PYROXENE GROUP.

The pyroxenes are silicates of iron, magnesia and lime, the lime predominating over the magnesia: the bases alumina, manganese, sodium and lithium also occur in some varieties. They are unattacked by acids. Sp. G. = 3 – 3·5. Hardness = 5 – 6. Cleavage parallel to the prism (angle = 87°), very imperfect. The smaller angle between the prism-faces and the inferior degree of cleavage constitute the main points of distinction from hornblende. Under the microscope sections perpendicular to the vertical axis are octagonal, being bounded by the faces of the prism and of both pinacoids.

The pyroxenes may be divided into two groups:—the rhombic and the monoclinic pyroxenes.

1. Rhombic Pyroxenes.

Silicates of iron and magnesia—$(MgFe)O,SiO_2$.

According to the percentage of iron they contain, the following varieties may be distinguished:—

Enstatite, with less than 5% of FeO.
Bronzite 5 – 14% of FeO.
Hypersthene, above 14% of FeO.

Intensity of colour and pleochroism increase with the percentage of iron, enstatite being colourless and non-pleochroic in thin section, bronzite slightly coloured and pleochroic, and hypersthene strongly so. The most highly ferriferous variety has been termed **amblystegite.**

The rhombic pyroxenes are characterized by the possession of a fairly perfect pinacoidal cleavage, in addition to the prismatic cleavage common to all pyroxenes. In some varieties the pinacoidal cleavage surfaces have a sub-metallic (bronzy or coppery) lustre. This phenomenon is caused by reflection from the surfaces of innumerable parallel rods and flakes of foreign matter intercalated along these planes, and said to be of secondary origin.

Between crossed nicols the rhombic pyroxenes extinguish, of course, straight. The double refraction is not high, the colours being of low grade. The pleochroism of hypersthene is as follows:—a = sea-green, β = salmon-red, γ = reddish yellow.

They occur in various igneous rocks: diorites, porphyrites, andesites and some peridotites, and pass by alteration into a fibrous substance known as **bastite.**

2. Monoclinic Pyroxenes.

a. Brown Pyroxene.

Common Augite. Silicate of alumina, lime, magnesia and iron: $(CaMgFe)O,(AlFe)_2O_3,4SiO_2$. Sp. G. = 3·30 – 3·50. Hardness = 5–6. (See Fig. 14.)

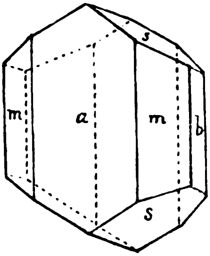

FIG. 14.

Crystal of Augite.
a. Orthopinacoid.
b. Clinopinacoid.
m. Prism.
s. Pyramid.
(*After Rosenbusch.*)

In thin section this mineral is of a pale-brown colour, sometimes with a violet tinge, especially when the mineral contains titanium. Pleochroism, faint or absent. Between crossed nicols fairly bright chromatic polarization. Extinction-angle, in sections parallel to the vertical axis, reaches a maximum of 45°. (Distinction from hornblende.) Slight variations in the extinction-angle in different peripheral layers often produce in the crystals a zonal structure, occasionally assuming the form of an hour-glass. (See Fig. 15.)

Dual and even multiple twinning (parallel to the orthopinacoid), not uncommon. (See Fig. 16.)

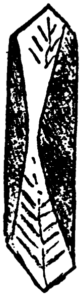

FIG. 15.

Crystal of Augite showing hour-glass structure
(*After Hatch.*)

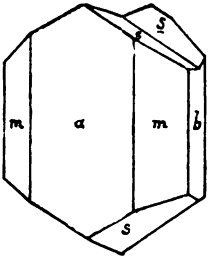

FIG. 16.

Crystal of Augite twinned on the Orthopinacoid.
a. Orthopinacoid.
b. Clinopinacoid.
m. Prism.
s. Pyramid.
(*After Rosenbusch.*)

Augite passes readily into chlorite by the ordinary process of weathering: dynamic metamorphism converts it into green hornblende (uralite, actinolite, etc.).

Loose crystals of black opaque augite occur among the material ejected from volcanoes (lapilli, cinders, ash, etc.). It is a very common constituent both of plutonic and volcanic rocks, especially of the more basic varieties: gabbro, dolerite, diabase, basalt, andesite, etc.

b. Green and White Pyroxenes.

Malacolite, Salite, Diopside, Coccolite, Omphacite. Silicates of lime, magnesia and iron. Sp. G. = 3·3.

In colour these augites vary from a very pale green (malacolite) to a bright grass-green (omphacite, chrome-diopside). Malacolite occurs in grains and prisms in certain diorites, epidiorites and metamorphic schists. Bright green augite (omphacite, chrome-diopside) occurs in some peridotites, also, in eclogite, pyroxene-granulite, etc.; coccolite occurs in metamorphic limestones.

Under the microscope malacolite gives colourless sections, which on account of their fairly high index of refraction (shown by strongly marked outline) and bright chromatic polarization, may easily be mistaken for epidote. It is distinguishable from this mineral, however, by obliquely extinguishing in lath-shaped sections, and by the absence of pleochroism.

Diallage is a laminated variety of augite, usually of a greenish colour, occurring in gabbro. The lamination is parallel to the orthopinacoid; it appears in thin section as a fine lineation, which constitutes the chief diagnostic character of the mineral. The faces of this lamination or pseudo-cleavage are characterized by a pearly or sub-metallic lustre. Thin pieces, flaked off in this direction and examined in convergent polarized light, present the oblique emergence of an optic axis (distinction from the rhombic pyroxenes).

c. Soda-pyroxene.

Aegirine and **Acmite** ($Na_2O,Fe_2O_3,4SiO_2$), corresponding to arfvedsonite, glaucophane, etc., among the hornblendes. They are of rare occurrence as rock-forming minerals, being found only in elæolite-syenite and certain phonolites and trachytes.

Olivine.—Silicate of iron and magnesia: $2(MgFe)O, SiO_2$. Rhombic. Occurs in tabular or prismatic forms, made up of pinacoids and domes, or in irregular grains. Sp. G. = 3·2–3·5. Hardness = 6·5–7. Gelatinizes with hydrochloric acid. Colour, olive-green to yellow. Pinacoidal cleavage, imperfect. Under the microscope olivine presents colourless sections, sometimes bounded by crystallographic contours, oftener by irregular and indented outlines, due to corrosion. (See Fig. 17.)

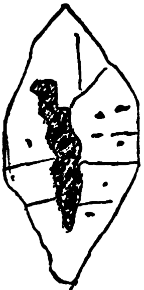

FIG. 17.

Corroded crystal of Olivine.
(*After Hatch.*)

Its index of refraction is high, the outlines being strongly marked and the surface of the sections having a roughened appearance. The double refraction is also high, the sections polarizing in bright colours. Straight extinction in all principal sections. Interpenetration-twins are not infrequent in basalt. (See Fig. 18.) They become visible between crossed nicols on account of the difference in extinction shown by the two individuals.

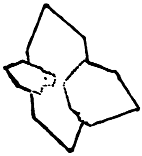

FIG. 18.
Twin-crystal of Olivine.
(*After Hatch.*)

Olivine occurs only in basic and ultrabasic rocks: in gabbros, diabase, dolerites, basalts, etc. The peridotites are mainly composed of this mineral. Olivine alters readily into fibrous aggregates of serpentine; the alteration proceeding along cracks, and being often accompanied by a separation of iron-ores (magnetite, limonite, etc.).

Haüyne and **Nosean.**—Silicates of alumina, lime and soda, together with sulphate of lime or soda. Regular. Sp. G. = 2·27–2·50. Hardness = 5 – 5·5. Gelatinizes easily with hydrochloric acid; on evaporation, needles of gypsum are formed in the case of haüyne, none in the case of nosean. The minerals are very similar in composition and appearance. Haüyne, however, is generally blue, and nosean, colourless or yellow. They are essentially volcanic minerals, occurring as sporadic grains in phonolites, andesites and basalt; also in volcanic ejectamenta (Vesuvius, Lake Laach in the Eifel).

Under the microscope they present square or six-sided sections, which remain dark when rotated between crossed nicols. The sections are characterized by the presence of numerous minute inclusions aggregated to a marginal or zonal dark band, or accumulated in the centre as a grey shaded patch. In other cases they are arranged along axes intersecting in the centre at 60°. (See Fig. 19.)

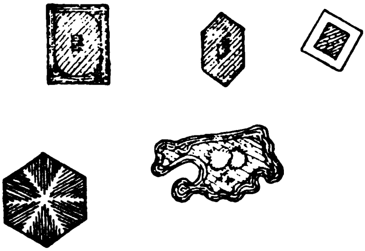

FIG. 19.

Crystals of Haüyne, showing the mode of arrangement of the inclusions. (*After Rosenbusch.*)

Scapolite. Silicate of alumina, lime and soda, + sodium chloride. Tetragonal. Sp. G. = 2·6 – 2·8. Hardness = 5–5·5. Colourless. Of infrequent occurrence in igneous rocks: oftener in gneisses and crystalline schists. Under the microscope, occurs in irregular colourless grains, possessing a well-defined cleavage. Between crossed nicols, bright chromatic polarization. **Couseranite** and **dipyre** are varieties of this mineral.

Sodalite. Silicate of alumina and soda, + sodium chloride. Regular. Sp. G. = 2·1 – 2·3. Hardness = 5·5. Gelatinizes easily with hydrochloric acid.

Occurs in blue, greenish, or colourless grains in elæolite-syenite and in volcanic ejectamenta. Under the microscope it presents colourless sections, which remain dark when rotated between crossed nicols. Numerous inclusions.

Wollastonite. Silicate of lime: CaO,SiO_2. Monoclinic. Sp. G. = 2·78 – 2·9. Hardness = 4·5 – 5. Colourless. Occurs in rods, needles and fibres in metamorphic limestones and crystalline schists. Easily gelatinizes with hydrochloric acid.

Apatite. Phosphate of lime + chloride or fluoride of lime: $3(Ca_3P_2O_8) + Ca(ClF)_2$. Hexagonal. Sp. G. = 3 16 – 3·22. Hardness = 5. When fresh, colourless and glassy; altered varieties are dull green and red. Soluble in acids without gelatinization; the nitric acid solution gives a yellow precipitate with ammonium molybdate (distinction from nepheline). Apatite occurs in long hexagonal prisms and needles; also in short prisms. It is one of the commonest accessory minerals, being found in most igneous rocks. It is especially abundant in the greenstones (dolerites and diabases), and the basalts. It is also one of the earliest-formed constitutents; for its needles are found penetrating all other minerals. Under the microscope it is colourless and presents six-sided cross sections and elongated lath-shaped longitudinal sections. The former remain dark when rotated between crossed nicols, the latter extinguish straight. Double refraction weak, the polarization colour being grey. There is often a central core of inclusions; and in such cases there is usually a slight absorption of light when the long axis of the section is parallel to the short diagonal of the nicol. Apatite may be easily mistaken for nepheline. It is distinguished from this mineral by the chemical reactions mentioned above, and by the fact that apatite occurs in long needle-like prisms, nepheline, on the other hand, in shorter and thicker prisms.

IRON-ORES.

The iron-ores that occur as common accessory constituents of rocks are magnetite or magnetic iron-ore, ilmenite or titaniferous iron-ore and pyrites.

Magnetite. Magnetic oxide of iron: FeO,Fe_2O_3. Regular. Sp. G. = 4·9 – 5·2. Hardness = 5·5 – 6·5.

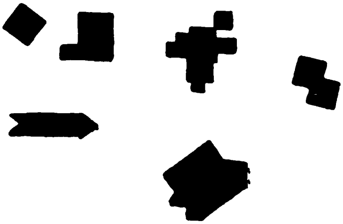

FIG. 20.

Crystals of Magnetite. (*After Rosenbusch.*)

One of the commonest accessory constituents of igneous rocks, especially of the basic type (*e.g.*, basalt), occurring in black octahedral grains. Under the microscope it is perfectly opaque, even in the thinnest sections. In reflected light it has a bluish-black metallic lustre (distinction from pyrites and ilmenite). (See Fig. 20).

Ilmenite. Titaniferous oxide of iron: $(TiFe)_2O_3$. Rhombohedral. Sp.G. = 4·5 – 5·2. Hardness = 5 – 6. Infusible. Attacked with difficulty by acids. Black and opaque in thin section. Occurs in hexagonal sections, but often in irregular grains, and then not easy to distinguish from magnetite. It may be distinguished from that mineral, however, by the fact that it is very liable to alteration into a white opaque substance, known as leucoxene (a variety of sphene), by which it is almost invariably accompanied. The alteration takes place along three systems of lamellæ intersecting at 60°, thus indicating the rhombohedral character of the mineral. Ilmenite occurs in basic igneous rocks especially in gabbro, dolerite and diabase.

Pyrites. Sulphide of iron: FeS_2. Regular, in cubes and pentagonal dodecahedra. Sp. G. = 4·9 – 5·2. Hardness = 6 – 6·5. Occurs abundantly disseminated in minute yellow specks and grains in both igneous and sedimentary rocks.

Under the microscope, it is opaque; in reflected light, however, its brassy yellow colour at once characterizes it.

Spinels. The spinel group consists of a series of minerals crystallizing in the regular system and composed of a double molecule formed by the union of a sesquioxide ($Fe_2O_3, Al_2O_3, Cr_2O_3$) with a protoxide ($FeO, MgO, MnO, ZnO, CrO$).

The commonest combinations occurring in rocks are the following:—[1]

	Formula.	Colour.	Sp. G.	H.
Spinel .	MgO, Al_2O_3	red	3·5–4·1	8
Pleonaste	$(MgFe)O, (AlFe)_2O_3$	dark green	3·6	8
Hercynite	FeO, Al_2O_3	,,	3·9	7·5–8
Picotite	$(FeMg)O, (CrAl)_2O_3$	yellowish brown	4·0	8
Chromite	$(FeMgCr)O, (CrAlFe)_2O_3$	dark brown to opaque	4·8	5·5
Magnetite	FeO, Fe_2O_3	black and opaque	4·9–5·2	5·5–6·5

The spinels are abundant in igneous and metamorphic rocks, occurring in small grains and octahedral crystals. Under the microscope they are isotropic (exerting no influence on polarized light). The dark-coloured spinels (pleonaste, hercynite, picotite and chromite) occur frequently in peridotites and serpentines. Magnetite has already been described with the iron-ores.

Garnets. Silicates of alumina, iron, manganese, chromium, lime and magnesia, having the general formula $3MO, R_2O_3, 3SiO_2$. According to the variation of MO and R_2O_3, the following varieties may be distinguished:[1]

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[1] Lévy and Lacroix.

	MO	R_2O_3	Colour.	Sp. G.
Grossularia	CaO	Al_2O_3	pale green	3·4–3·6
Almandine	FeO	Al_2O_3	claret	3·5–4·3
Pyrope	FeO, MgO, CaO	Al_2O_3, Cr_2O_3	blood red	3·7–3·8
Melanite	CaO	Fe_2O_3	blackish brown	3·6–4·3
Spessartine	MnO	Al_2O_3	light reddish	3·7–4·3
Ouvarovite	CaO	Cr_2O_3	green	3·4–3·5

Other garnets consist of mixtures of these molecules. Insoluble in acids. Hardness $=6{\cdot}5–7{\cdot}5$.

The garnets crystallize in the Regular System, the most common form being the rhombic dodecahedron, the edges of which are sometimes truncated by icositetrahedral faces.

Under the microscope garnet appears in irregular or in 4- and 6-sided grains of a pink or salmon colour. Rotated between crossed nicols they remain dark; in exceptional cases, however, they are "optically anomalous," giving evidence of double refraction in a feeble transmission of light between crossed nicols. The sections are traversed by irregularly branching cracks produced by an imperfect cleavage parallel to the rhombic dodecahedron. The index of refraction is fairly high, giving the grains bold contours.

As an accessory constituent, garnet is common enough, occurring in granites and microgranites (granulite, aplite), in the gneisses and crystalline schists, and in the sands produced by the disintegration of these and similar rocks. It is constant in its occurrence in some of the peridotites and allied rocks: eclogite, pyroxene-granulite, etc.

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[1] Lévy and Lacroix.

Zircon. Silicate of zirconium: ZrO_2,SiO_2. Tetragonal, occurring in small prisms terminated at both ends by the pyramid. Colour, red and brown. Infusible; unattacked by acids. Sp.G. = 4·4–4·7. Hardness = 7·5. In thin sections zircon occurs in small, colourless grains, with well-marked contours. Between crossed nicols the polarization colours are brilliant pinks and greens, the double refraction being high.

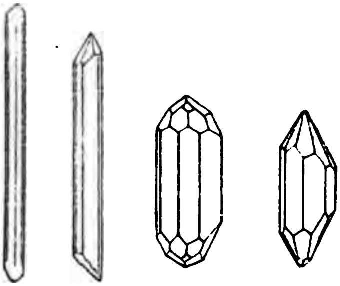

FIG. 21.
Crystals of Zircon. (*After Rosenbusch.*)

Zircon has a wide distribution in eruptive (both plutonic and volcanic) and metamorphic rocks, occurring frequently as an inclusion in black mica, in which case the grains are surrounded by a pleochroic zone. Being undecomposable it is found in the sands derived from granitic and gneissose rocks, and also in the sandstones and quartzites produced by their consolidation. (See Fig. 21.)

Rutile. Titanic Oxide : TiO_2. Tetragonal, crystallizing in slender prisms and needles. Frequently twinned, on two types, producing geniculated and heart-shaped forms. Colour, yellow to red. Sp. G. = 4·20 – 4·27. Hardness = 6 – 6·5. Unattacked by acids. Distinguished under the microscope by its yellow colour and strongly marked borders, due to the high index of refraction it possesses. It frequently presents a peculiar interlaced structure, known as *sagenite* (see Fig. 22). Rutile occurs as prisms and twins in the crystalline schists, especially in hornblende-schist; also in sands and sedimentary rocks. Fine hair-like bodies occurring in quartz and clay-slates (*Thonschiefernädelchen*), are referred to rutile.

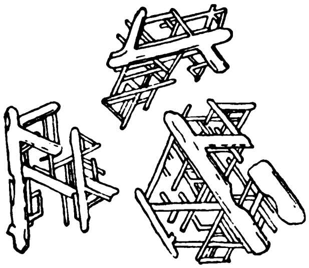

FIG. 22.
Crystals of Rutile (Sagenite). (*After Rosenbusch.*)

Tourmaline. A complicated silicate and borate of alumina, magnesia and iron. Rhombohedral, occurring in triangular prisms with rhombohedral termination. The prisms show a vertical striation. Often fibrous, in veins and stellate aggregations. Sp. G. = 2·94 – 3·24 Hardness = 7 – 7·5. Unattacked by acids. Colour usually black. Vitreous lustre. Under the microscope, the lath-shaped, prismatic sections extinguish straight. Marked pleochroism in violet, blue, green and brown colours; the deeper colour always appearing when the long axis of the section is perpendicular to the short diagonal of the polarizing nicol (distinction from biotite). The variety schorl occurs in micrograuites (*e.g.*, the elvans of Devon and Cornwall), in the marginal portion of granites (schorlaceous granite), and in the altered rock in contact with granite (schorl-rock). It also occurs in pegmatite veins. (See Fig. 23.)

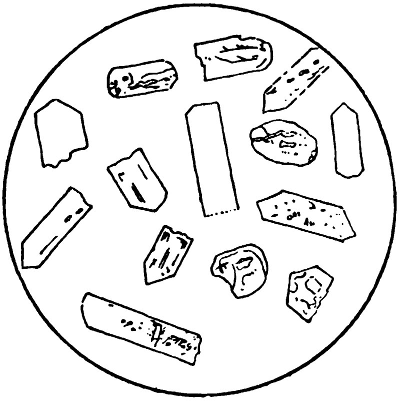

FIG. 23.

Crystals of Tourmaline, from the Bagshot Sands at Hampstead, under tho microscope. (*After Teall.*)

Sphene. Silicate and titanate of lime: CaO,SiO_2, TiO_2. Monoclinic. In flat cuneate crystals of a greenish yellow to blackish-brown colour. Sp. G. = 3·3–3·7. Hardness = 5–5·5. Unattacked by hydrochloric acid.

Under the microscope sphene appears in irregular strongly contoured grains, which are occasionally wedge-shaped. Its colour, in thin section, is reddish-yellow. Pleochroism feeble. Double refraction very high, but not producing brilliant characteristic polarization, the colour effect between crossed nicols being an indefinite grey. The white opaque substance surrounding ilmenite, and resulting from its alteration, is a variety of sphene known as **leucoxene.**

Sphene occurs in granites, syenites and crystalline schists; leucoxene in gabbros, diabases, epidiorites and hornblende and chlorite schists.

Epidote. Silicate of lime, alumina and iron: $H_2O,4CaO,3(AlFe)_2O_3,6SiO_2$ Monoclinic, in crystals elongated parallel to the orthodiagonal axis. Lath-shaped sections therefore give straight extinction between crossed nicols. Sp. G. = 3·39. Hardness = 6–7. Unattacked by hydrochloric acid. Colour, yellowish-green. Perfect cleavage parallel to the basal plane. Epidote occurs as a frequent alteration-product of the ferromagnesian minerals, in gabbros, diabases, diorites, melaphyres, epidiorites and hornblendic and chloritic schists. It is also found veining these rocks, or associated with other secondary minerals in the amygdules of old lavas. Under the microscope it appears in small colourless to yellow grains or prisms. When coloured it is faintly pleochroic. Brilliant chromatic polarization between crossed nicols. **Piedmontite** (withamite) is a red, markedly pleochroic, variety of epidote occurring in the Glencoe porphyrite (Scotland), in the famous *Porfido rosso antico* of Egypt, and in certain Japanese mica-schists (Piedmontite-schist).

Zoisite. Silicate of lime and alumina: $H_2O, 4CaO, 3Al_2O_3, 6SiO_2$. Rhombic, occurring usually in columnar aggregates of a whitish-grey colour. Sp. G. = 3·25–3·36. Hardness = 6. Unattacked by hydrochloric acid. Under the microscope it presents colourless prisms and granules, resembling epidote, but distinguishable from that mineral by its low double refraction, a feeble bluish light being transmitted between crossed nicols. Occurs in association with epidote in altered basic igneous rocks and metamorphic schists.

CARBONATES.

The carbonates of lime, lime-magnesia and iron (calcite, dolomite and siderite) are isomorphous, and can replace one another in any proportions.

Calcite. Carbonate of lime: $CaCO_3$. Rhombohedral. The crystalline forms assumed by calcite are innumerable: it occurs in rhombohedra, which may be either flat or have any degree of acuteness; in sharp-pointed scalenohedra (dog-tooth spar); in thick-set six-sided prisms crowned by the faces of the rhombohedron; or in slender prisms terminated by the basal plane. It also occurs in amorphous masses and in veins. Sp. G. = 2·72. Hardness = 3 (easily scratched with the knife). Cleavage parallel to the rhombohedron, perfect rhombohedra being produced by the fracture. Effervesces with acids in the cold. Colourless to white, but often stained yellow, red and brown by ferruginous impurities. Under the microscope it occurs in irregular grains, traversed by fine cleavage lines, intersecting at an acute angle. Between crossed nicols, the polarization colour is an iridescent pinkish grey;

and broad colour-bands, produced by lamellar twinning, are often visible.

As a secondary constituent, calcite occurs in the more basic igneous rocks,—diorites, gabbros, diabases, etc. It is the principal constituent of the altered limestones (marbles). It often forms the cementing material of elastic rocks (*e.g.*, calcareous sandstones).

Aragonite is the rhombic carbonate of lime. Its crystals are often six-sided, resembling the hexagonal combination of prism and basal plane. Sp. G. = 2·9–3. Hardness = 3·5–4. It is found in fibrous and spherulitic aggregates in many igneous and metamorphic rocks. It frequently fills cavities in basalt, or traverses the same rock in strings and veins. Stalactites are often built up of fibrous aggregates of aragonite. The small spherular bodies formed in warm calcareous springs and giving rise to pisolitic and oolitic rocks, consist of radiate and fibrous aragonite.

Zeolites. A group of hydrated silicates of various bases: alumina, potash, soda, lime, baryta and strontia. They are secondary products, occurring in igneous rocks as the infillings of amygdaloidal cavities (especially of melaphyres and basalts), or as pseudomorphs after decomposed minerals (*e.g.*, nepheline).

Under the microscope they are always colourless, and occur in fibrous and radiate aggregates. They are easily decomposed by hydrochloric acid, with separation of gelatinous silica.

Some of the more commonly occurring varieties are: natrolite (or mesotype), analcime, phillipsite, prehnite, scolecite and apophyllite.

Chlorites.[1] Hydrated silicates of magnesia, iron and alumina. Monoclinic (pseudo-hexagonal). Gelatinize with hydrochloric acid. Sp. G. = 2·60 – 2·96. Hardness = 1 – 1·5. Colour, green: pleochroic in green and yellow tints. Occur in six-sided plates and scales, sometimes united in spherular and spiral aggregates (delessite and helminth). Basal cleavage, less perfect than in mica; cleavage-flakes non-elastic. The double refraction is low, the usual colour between crossed nicols being a grey or steel-blue of the first order.

Chlorite is essentially a secondary mineral resulting from the decomposition of dark mica, hornblende and augite. It occurs abundantly in altered igneous rocks, especially in the more basic types—gabbro, diabase, melaphyre, etc., which largely owe their greenish colour to this mineral; also in epidiorites and chlorite-schists. It is sometimes confused with secondary hornblende and with serpentine, with which it is often associated and which it much resembles. It may be distinguished, under the microscope, from the former by its low double refraction, and from the latter by its pleochroism.

Viridite is an indefinite name given to the various green alteration products (chlorite, serpentine, etc.) occurring in diabase.

Ottrelite and **Chloritoid.** Hydrated silicates of alumina, magnesia, iron and sometimes manganese. Monoclinic, but with pseudo-hexagonal symmetry, Sp. G. = 3·52 – 3·57. Hardness = 6·5. Colour, bluish-green. Pleochroism in bluish and green tints. Occur in lustrous 6-sided plates in metamorphic schists. Under the microscope, characterized by lamellar twinning.

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[1] Under the name of chlorite is included a number of allied minerals, differing but slightly from one another in regard to their optic properties (*pennine, ripidolite, helminth, clinochlore, kämmererite, metachlorite, delessite, chlorophæite*).

Serpentine. Hydrated silicate of magnesia and iron : $2H_2O,3(MgFe)O,2SiO_2$. Sp. G. = 2·5 – 2·7. Hardness = 3 – 4. Colour, dull green; often stained red and yellow with iron oxides. Occurs most frequently as an alteration-product of olivine, less frequently of hornblende and augite. Under the microscope it usually presents a confusedly interlaced aggregate of colourless blades, scales and fibres, which frequently enclose unaltered fragments of the mineral from the alteration of which it takes its origin (see Figs. 24 and 25). Serpentine derived from olivine, is

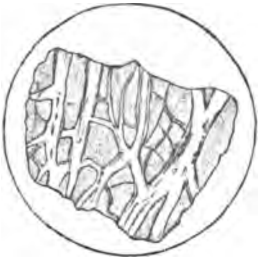

FIG. 24.

Serpentine.
(After Bonney.)

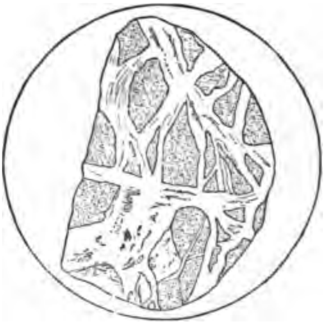

FIG. 25.

Serpentine.
(After Bonney.)

said to possess a "mesh-structure"; that arising from the alteration of hornblende is more "bladed"; while augite gives rise to a "netted" form of the mineral. These different structures are produced by the variable nature of the cleavages in these minerals, the alteration into serpentine invariably proceeding along these planes of weakness. Serpentine also occurs massive, and may then be considered as a rock.

Kaolinite. Hydrated silicate of alumina: $2H_2O, Al_2O_3, 2SiO_2$. Rhombic, but with pseudo-hexagonal symmetry. Sp. G. = 2·34 – 2·57. Hardness = 1 – 2. Dissolved by boiling sulphuric acid.

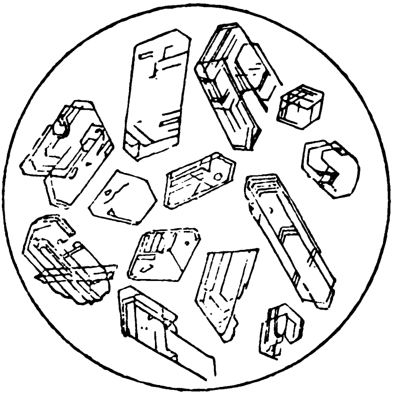

FIG. 26.

Crystals of Kaolinite, under the microscope. (*After Teall.*)

Occurs in colourless six-sided plates and scales as an alteration-product of felspar; and the turbidity of altered felspar is chiefly due to the development of this mineral. It is the chief constituent of china-clay, or kaolin. (See Fig. 26.)

Talc. Hydrated silicate of alumina: $H_2O, 3MgO, 4SiO_2$. Rhombic, but with pseudo-hexagonal symmetry. Sp. G. = 2·7 – 2·8. Hardness = 1. Scratched by the finger-nail. Pale green or colourless. Cleavage, basal. Flakes flexible but non-elastic.

Occurs, in thin section, in colourless scales, giving brilliant chromatic polarization between crossed nicols, and resembling muscovite. It occurs as an alteration-product of magnesian minerals, mainly in metamorphic schists (talc-schist).

Andalusite. Silicate of alumina: Al_2O_3, SiO_2. Rhombic. In square thick-set prisms, terminated by the basal plane. Sp. G. = 3·1 – 3·2. Hardness = 7–7·5. Unattacked by acids.

Crystals of this mineral usually appear dark-coloured owing to the presence of included graphite. Under the microscope, however, the grains are either colourless or pink; in the latter case, they often present a marked pleochroism (yellow to red). The pleochroism is sometimes manifested in irregularly distributed spots and patches.

Occurs in slates and shales that have undergone extreme metamorphism in contact with granite; also in crystalline schists. **Sillimanite**, or **fibrolite**, is a fibrous variety of andalusite occurring in gneisses.

Chiastolite is a variety of andalusite, containing graphitic material arranged along the diagonals of the prisms. Occurs in small light-coloured prisms in chiastolite-slate, in the immediate neighbourhood of granite.

Staurolite. Silicate of alumina and iron: $FeO, 2Al_2O_3, 2SiO_2$. Rhombic. In prismatic forms terminated by the basal plane; commonly twinned, forming symmetrical Maltese and St. Andrew's crosses. Sp. G. = 3·3 – 3·8. Hardness = 7 – 7·5. Unattacked by acids. Occurs in the crystalline schists, and in rocks of the granite contact-zone.

Cordierite. Silicate of alumina, iron and magnesia: $3MgO,3(AlFe)_2O_3,8SiO_2$. Rhombic, with pseudo-hexagonal symmetry. Sp. G. = 2·60 – 2·66. Hardness = 7 – 7·5. Often twinned. Colour, dark blue; in thin section usually colourless. Feeble pleochroism when coloured. Yellow pleochroic spots or halos round inclusions of zircon and apatite, which disappear on rotation of the section.

Cordierite may be distinguished from andalusite by its lower index of refraction, a grain placed in Canada balsam being scarcely visible, whereas andalusite stands out with well-marked contours.

This mineral occurs in granite and gneiss (cordierite-gneiss); more rarely in volcanic rocks (*e.g.*, basalt, andesite). It alters easily into mica-like decomposition products (pinite, esmarkite, praseolite, gigantolite, etc.).

Idocrase. (Vesuvianite). Silicate of lime and alumina: $H_2O, 8CaO, 2Al_2O_3, 7SiO_2$. Tetragonal. In square prisms terminated by a pyramid. Sp. G. = 3·3 – 3·4. Hardness = 6·5. Colour, dark green, brown, red, yellow. Vitreous lustre. Occurs in limestones that have undergone alteration by contact with igneous rocks.

IV.

THE STRUCTURE, CHEMICAL COMPOSITION AND ALTERATION OF THE IGNEOUS ROCKS.

1. STRUCTURE.

The igneous rocks, with the exception of those of pyroclastic origin (tuffs, volcanic ash, etc.), are **massive**, *i.e.*, they are **unstratified**. Parallel structures, that simulate bedding, are, however, sometimes found in them. These are produced by jointing in plutonic rocks (*e.g.*, granite), and by flow in volcanic rocks. But little real difficulty is experienced in distinguishing between true and simulated stratification.

With regard to internal structure, the plutonic rocks are, as a rule, **holocrystalline**, *i.e.*, they are composed wholly of crystalline material, no interstitial glassy or felsitic matter being present in them.

In rocks in which the minerals are developed simultaneously, the crystals mutually impede one another's growth, so that the grains, for the most part, cannot assume crystallographic outlines. Such grains are said to be **allotriomorphic**. When, however, a mineral gets the start of its fellows, well-contoured crystals may be formed. Such a mineral is said to be **idiomorphic** with regard to the others.

In respect to the size of the grain, the structure of a holocrystalline rock may be **coarsely crystalline, finely crystalline**, or **microcrystalline.** These terms explain themselves. An apparently homogeneous rock is sometimes found, when examined in thin sections under the microscope, to split up into an aggregate of minute granules, which act upon polarized light but are too small for even microscopic determination.

The following internal structures and textures are presented by igneous rocks :—

Granitoid—a more or less coarse-grained and holocrystalline texture, the grains being of tolerably uniform size and, for the most part, without crystalline contours (allotriomorphic). This texture is presented by deep-seated or plutonic masses,—the granites, syenites, diorites, gabbros, etc.

Porphyritic.—In some intrusive and in most volcanic rocks there are two distinct phases of crystallization. The first phase consists in the formation of large or "porphyritic" crystals, which float in the molten magma and are sometimes corroded by it. This phase has been termed the *intra-telluric phase of crystallization,* because the crystals are produced before the eruption of the rock, while it is still in the interior. The second phase consists in the consolidation of the magma. This becomes the *groundmass* in which the "porphyritic constituent"[1] is imbedded. The ground-mass usually contains a second crop of small crystals of the same mineral as the porphyritic constituent, together with the remaining minerals. If the crystallization is complete, the ground-mass is holocrystalline. More usually, however, a "residuum of crystallization," or mother-liquor, remains after the separation of the crystalline elements, and consolidates as interstitial glassy matter. This is termed the *glassy base.* If the rock is subsequently exposed to meteoric influence, devitrification takes place, and the glassy base is replaced by a *felsitic base,* or cryptocrystalline aggregate of quartz and felspar. A similar substance is sometimes developed during consolidation.

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[1] Iddings suggests the term *phenocryst* for the porphyritic constituent (Ger.=Einsprengling).

Granophyric.—In certain granites (granophyres) the larger crystals are embedded in a ground-mass consisting of *micropegmatite, i.e.,* an intimate but regular intergrowth of quartz and felspar. This is termed the granophyric structure.

Ophitic—a structure shown by most dolerites, and some gabbros. The felspar in these rocks appears to have been formed at a slightly earlier period than the augite; in consequence of which the felspar appears in well-contoured lath-shaped crystals, while the augite plays the *rôle* of ground-mass, enveloping and being penetrated by the felspar. In rare instances the reverse is found to be the case, the felspar being present as a matrix in which lie well-formed crystals of augite.

Vitreous.—Rocks that have cooled suddenly are composed entirely or in great measure of glass. Sometimes it is the whole body of the rock that is vitreous, sometimes only a narrow "selvage" that has come into immediate contact with the cooling surface. This natural glass is, however, seldom completely devoid of crystalline material. Examined with the microscope, it is often found to contain numerous minute, spherical, rod-shaped, and hair-like bodies, which represent the first products of crystallization. These bodies are in general termed *crystallites.* They are not crystals, for they possess no distinct crystallographic form, nor do they react on polarized light. The different forms have received specific names: the drop-like bodies are termed *globulites*; the rod-shaped ones, *belonites*; and the coiled and twisted hairs, *trichites.* (See Fig. 27.)

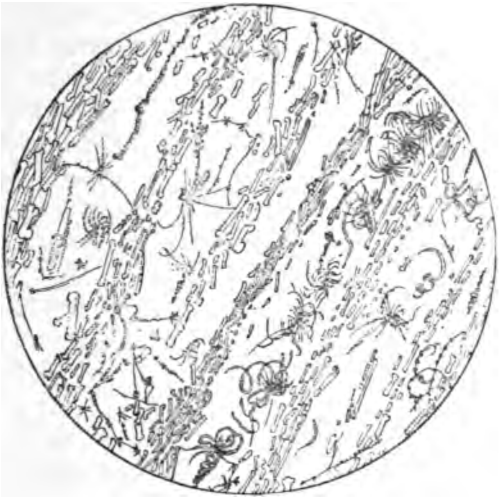

FIG. 27.

Obsidian, with bands of microlites and trichites, under the microscope. The linear arrangement is due to flow during consolidation. (*After Fouqué and Lévy.*)

Besides these bodies there exist small needle- and rod-shaped bodies which are known as *microlites*. They are distinguished from crystallites by the fact that they do react on polarized light (becoming alternately light and dark when rotated between crossed nicols), and can generally be referred to some mineral species —felspar, augite, olivine, magnetite, etc. By combination of the simple microlitic forms, curiously forked and gridiron-like aggregates (*skeleton-crystals*) are produced (see Fig. 28 and Fig. 29). The linear arrangement of these various elementary bodies, and the way in which they sweep round the larger crystals, serve to indicate the once fluid nature of the vitreous rocks in which they are found (*fluxion-* or *flow-structure*). (See Fig. 27 and Fig 30.)

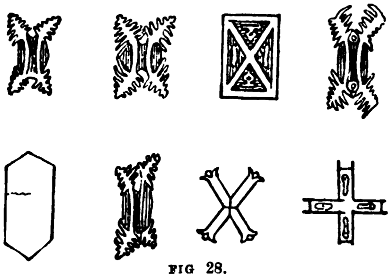

FIG 28.
Skeleton crystals of Olivine. (*After Rosenbusch.*)

An incipient form of crystallization often met with in vitreous rocks consists in the production of small spherical bodies, known as *spherulites*. These bodies, which vary in size from a millet-seed to a pea, present, when viewed under the microscope, a divergent fibrous structure, and are characterized between crossed nicols

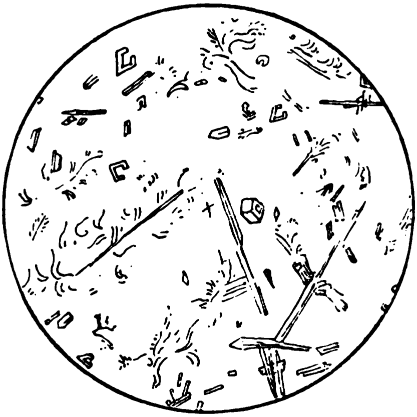

FIG. 29.

Pitchstone of Arran, under the microscope, showing microlites and skeleton-crystals of Hornblende in a glassy base. (*After Teall.*)

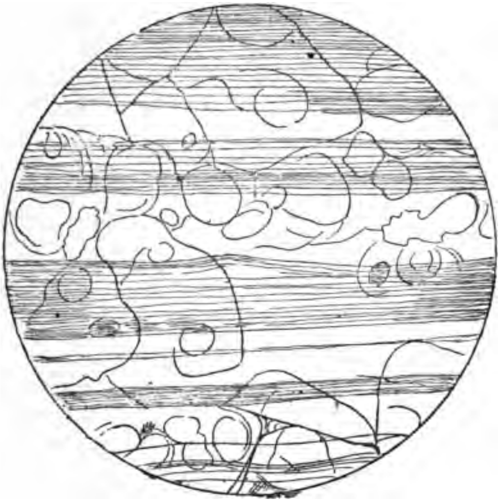

FIG. 30.

Perlite of Tokay, Hungary, under the microscope, illustrating Perlitic and Flow Structure. (*After Fouqué and Lévy.*)

by a black cross, the arms of which are parallel to the short diagonals of the two nicols. With regard to spherulites, Allport (*Q. J. G. S.*, xxxiii., p. 452) says: "These semi-crystalline bodies were evidently the last substances formed prior to the solidification of the mass; for not only are the more perfectly crystallized constituents (felspar, mica, etc.) enclosed in them, but even the streams of microlites also occasionally pass straight through them. These crystals first form in a viscous glassy magma, which was also crowded with innumerable microlites; before the mass consolidated the fluidal structure was imparted to it; and subsequently during solidification the radiating spherulites were formed, without disturbing the previous arrangement of the microlites." (See Fig. 31 and Fig. 32.)

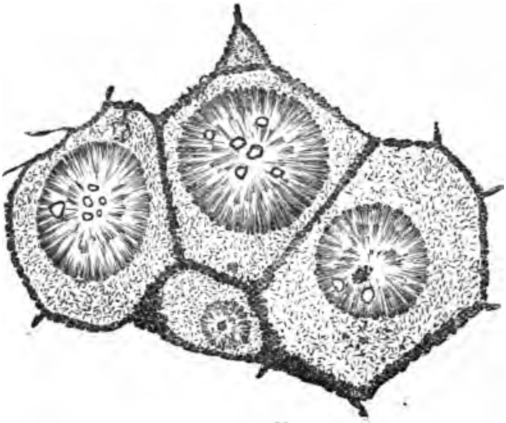
FIG. 31.
Spherulitic Structure in a Felsite of Arran.
(*After Bonney.*)

Vitreous rocks are further characterized by the

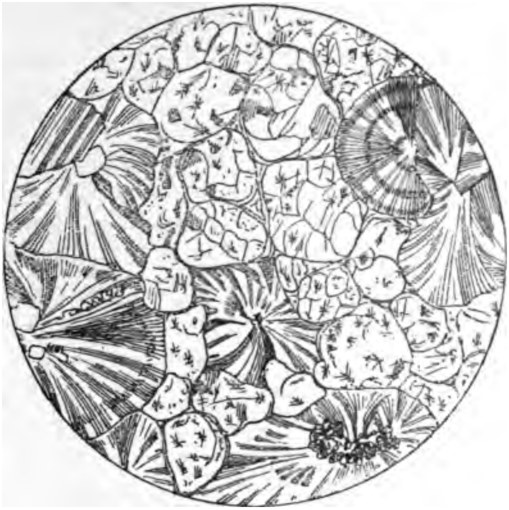

FIG. 32.
Spherulitic Structure, between crossed nicols. (*After Fouqué and Lévy.*)

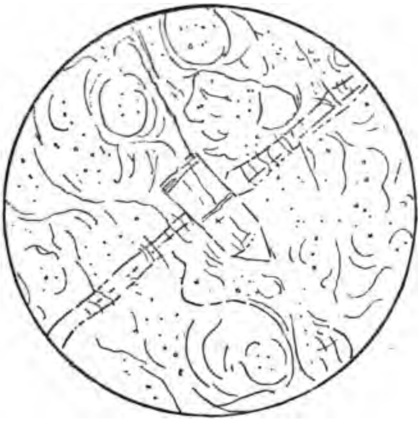

FIG. 33.
Pitchstone of Eigg, under the microscope, showing Perlitic Structure. The central crystal is Sanidine. (*After Teall.*)

frequent presence of a globular structure due to concentric fissuring around central points, producing a laminar structure similar to that presented by an onion. This is known as the *perlitic structure* (see Fig. 33 and Fig. 30). Its origin is ascribed to contraction on cooling.

The presence of either spherulitic or perlitic structure in a rock is a sure sign that it originally consolidated as a glass.

Cellular and **vesicular structures** are produced in volcanic rocks by the expansion, on eruption, of the steam dissolved in them.

The vesicles are usually elongated by the flow of the rock, and they are then said to be *amygdaloidal* (almond-shaped). They form convenient receptacles for the mineral matter precipitated from the waters that are in constant circulation through rocks.

2. COMPOSITION.

In respect to chemical composition, igneous rocks fall naturally into four groups, viz :—

(1) **An acid group** with 65 to 80% of silica, Sp. G. below 2·75 ; *e.g.*, granites, elvans, rhyolites, felsites.

(2) **An intermediate group** with 55–70% of silica, and Sp. G. between 2·70 and 2·80; *e.g.*, syenites, diorites, trachytes, andesites, porphyrites.

(3) **A basic group** with 45–60% of silica, and Sp. G. between 2·80 and 3·00 ; *e.g.*, gabbros, dolerites, basalts, melaphyres and pyroxenites, hornblendites, magma-basalts, etc.

(4) **An ultrabasic group** with silica between 35

and 50%, and Sp. G. between 2·85 and 3·4; *e.g.*, picrites, peridotites.

The acid group is characterized by the presence of free silica or quartz in greater or less abundance. The dominant felspar is orthoclase; but plagioclase also occurs. The intermediate group comprises rocks with little or no quartz, and in which plagioclase felspar is more abundantly developed than orthoclase. In the basic rocks quartz is absent, and orthoclase generally so. Olivine, on the other hand, is frequently present. The pyroxenites,hornblendites and magma-basalts, constitute a type of basic rock in which both felspar and olivine are absent. Lastly, the ultrabasic rocks contain little or no felspar, and consist for the greater part of olivine. With regard to hornblende and augite, the former has a predilection for the more acid rocks, while the latter favours the basic rocks; but this rule does not always hold good.

Rocks belonging to the acid group are in general of a light colour. As the basic character increases they become darker in colour, owing to the greater abundance of ferro-magnesian minerals and iron-ores. The specific gravity also increases with the basicity, being about 2·6 in acid rocks, and reaching as much as 3·6 in ultrabasic varieties.

3. ALTERATION.

When exposed to meteoric and solfataric influences (weather, percolating thermal waters, gaseous exhalations, etc., etc.), igneous rocks undergo marked changes: the felspars, originally glassy, perhaps, become opaque or turbid, due to the development of kaolin; the ferro-magnesian minerals yield chloritic, serpentinous and ferruginous products; lime-bearing minerals produce calcite, epidote, etc. These secondary minerals are deposited in fissures and cavities, forming veins and amygdules of calcite, epidote, chlorite, serpentine, zeolites, chalcedony, opal and even quartz. By the infiltration of material from without, the composition of a rock may be considerably changed. Thus the percentage of silica in some andesites is known to have been raised by the introduction of chalcedonic and opaline silica.

By processes of this nature the character of a rock is often much modified: vesicular rocks get their cavities in-filled; vitreous rocks become dull and stony, devitrified in fact; a fresh rock, in which the mineral structure and composition are easily discernible, becomes converted into a "weathered" and decayed mass, which can only with the greatest difficulty be referred to its proper category. In consequence of this we find altered and fresh varieties of rocks, identical in composition, structure and mode of origin, designated by different names. Thus dolerites, by alteration, are converted into diabases; rhyolites become felsites; andesites, porphyrites; and basalts, melaphyres.

V.

THE CLASSIFICATION AND DESCRIPTION OF THE IGNEOUS ROCKS.

To produce a satisfactory classification of the igneous rocks, a classification which shall be at once simple and comprehensive, is one of the most difficult problems a petrologist can attack. The various types are so intimately related, that any attempt at rigid and systematic classification is not likely to meet with any great measure of success. What is required is an elastic classification. In the arrangement adopted in these pages, chemical composition (as far as the percentage of silica is concerned) and mode of origin or occurrence, occupy a chief place. Mineralogical composition is, on account of its extreme variability, allowed to play only a subsidiary *rôle.*

The division into groups here adopted, is then founded on the proportion of silica present. Each group is subdivided into three families, the first of which embraces the more coarse-grained holocrystalline rocks, which have consolidated in deep-seated portions of the earth's crust; the second, the microcrystalline and porphyritic rocks, which, for the most part, have been injected into fissures or between bedding-planes; and the third, the sub-vitreous volcanic rocks. It must not be supposed that these divisions correspond to hard and fast lines in nature. On the contrary, every gradation exists from one to another (see p. 10). Both groups and families overlap. All that has been done, is to select a few convenient points around which to group allied types.

Acid Group.

1. The Granite Family.
2. The Elvan Family.
3. The Rhyolite Family.

Intermediate Group.

4. The Syenite and Diorite Family.
5. The Mica-trap and Lamprophyre Family.
6. The Trachyte and Andesite Family.

Basic Group.

7. The Gabbro Family.
8. The Dolerite Family.
9. The Basalt Family.

Appendix to Basic Group.

10. Pyroxenite and Hornblendite Family.
11. Magma-basalt Family.

Ultrabasic Group.

12. Peridotite and Serpentine Family.

1. THE GRANITE FAMILY.

The granites[1] are wholly crystalline aggregates of quartz, orthoclase and plagioclase, with one or more varieties of mica, hornblende or augite (see Fig. 34). According to the nature of the latter, the following varieties may be distinguished :—

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[1] The word granite was first used by Cæsalpinus in the year 1596.

Normal granite, with both light and dark mica.

Muscovite-granite, with white mica alone.

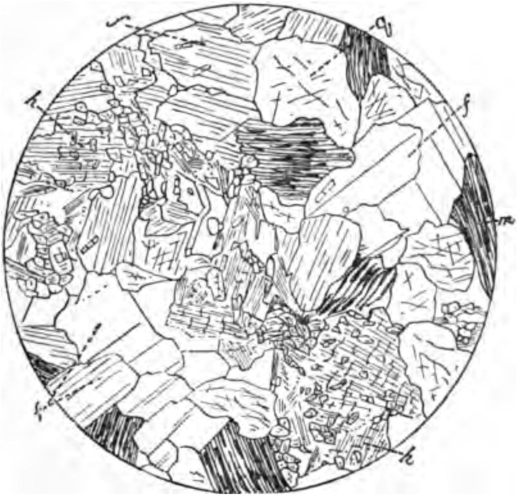

FIG. 34.
Granite (Hornblende-granite), under the microscope.
f. Felspar (orthoclase and plagioclase).
q. Quartz. *m.* Mica.
h. Hornblende, with granules of Epidote.
(*After Fouqué and Lévy.*)

Biotite-granite or **granitite,**[1] with dark mica alone.

Hornblende-granite or **hornblende-granitite,** with hornblende alone, or in addition to dark mica.

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[1] Granitite is the name given by Rose to a granite containing much oligoclase and black mica. But it is used as above by Rosenbusch.

Augite-granite, with augite in addition to black mica.

The essential minerals are present in approximately equal proportions. They can easily be distinguished in the hand-specimen. The quartz is recognisable by its vitreous lustre, pellucidity, conchoidal fracture and absence of cleavage. It is either colourless, or possesses a smoky tinge.

The orthoclase is usually the predominant mineral. It is generally of a pinkish colour and non-transparent. Its cleavage is well-marked, the cleavage planes being large and lustrous.

The crystals are usually twinned on the Carlsbad type, and the two halves can be readily distinguished by the opposed inclination of the cleavage surfaces. Under the microscope, the sections of orthoclase are seen to contain cumulous aggregates of kaolin, producing a characteristic turbidity. This is due to decomposition, and is known as "kaolinization." Very frequently orthoclase contains included patches and lamellæ of triclinic felspar, intercalated along orthopinacoidal planes. The resulting structure is known as *microperthite*. A common associate of the orthoclase is microcline, which is at once distinguished under the microscope by its characteristic cross-hatching.

The plagioclase is usually the soda-lime variety known as oligoclase. It occurs in less quantity than the orthoclase, and may generally be distinguished from it by its white or greenish-white colour; also by a fine parallel twin-striation, visible on the cleavage-faces.

The micas may be recognised by their extreme cleavability. The muscovite is silvery white, and the biotite brownish-black with metallic lustre. The hornblende is black or dark-green: it occurs in crystals which cleave parallel to the prism, the angle of which is 124°. The augite is a pale variety (malacolite).

Numerous accessory minerals occur in granite: apatite, zircon, sphene, orthite, garnet, topaz, cordierite (pinite), schorl (in schorlaceous granite), fluorspar (in trowlesworthite), molybdenite and iron-pyrites. Talc, chlorite, epidote and calcite are secondary minerals, resulting from decomposition.

The chemical composition of the granites varies according to the proportion of the ingredients. The following analysis expresses roughly the mean values:—

$SiO_2 = 72\%$, $Al_2O_3 = 16\%$, $FeO + Fe_2O_3 = 1{\cdot}5\%$, $CaO = 1{\cdot}5\%$, $MgO = 0{\cdot}5\%$, $K_2O = 6{\cdot}5\%$, $Na_2O = 2{\cdot}5\%$; Sp. G. $= 2{\cdot}59 - 2{\cdot}75$ (v. Lasaulx).

With regard to structure, there is also considerable variability; the commonest structure is that in which the minerals appear to have separated approximately simultaneously. They form then a holocrystalline "granitoid" aggregate, the boundary of each grain being formed by those of its immediate neighbours, to the exclusion of crystal faces. The size of the individual grain varies considerably, and accordingly we have fine-grained and coarse-grained granites. Many granites are coarse-grained in the interior of the mass, but pass into a fine-grained, or even microcrystalline variety, at the margin or in the apophyses sent off from the main mass, where the cooling has necessarily taken place more rapidly.

Some granites contain large porphyritic crystals of orthoclase. In such cases, the ground-mass has the composition of an ordinary granite, and contains a second crop of orthoclase-crystals. Such rocks are termed **granite-porphyry.**

In other granites there is a base of fine micropegmatite, surrounding the crystals of quartz and felspar. The surrounded grain is often in optical continuity with the quartz or felspar of the micropegmatite.

Granite often contains dark patches, in which the more basic minerals have segregated during consolidation. Such "concretionary patches" are known to the quarry men under the name of "heathen." In rarer instances, the constituents have assumed during consolidation a radial and concentric arrangement around certain smaller patches, producing **spheroidal** or **ball-granite.**

Granite occurs in large intrusive masses, bosses and laccolites, altering, and sending off veins or apophyses into, the slates in contact with it. The contact-zone extends around some of the large masses (*e.g.*, Mt. Leinster) to the distance of a mile away from the granite. Within the contact-zone the slates are crumpled and rendered crystalline. The characteristic contact-minerals in the slates are mica, schorl, chiastolite, andalusite, kyanite and staurolite. The chiastolite and andalusite first indicate their presence by the formation of spots and knots, producing the so-called spotted and knotted slates (*Fleck-, Frucht-* and *Garbenschiefer* of the Germans). Limestones in contact with granite are converted into marble, which generally contains one or more of the following lime-silicates wollastonite, idocrase, diopside, etc.

Granite, when subjected to dynamic metamorphism, assumes a foliated character, the quartz and felspar being drawn out into eye-like masses, the central part of which may consist of the original mineral, while the external layers are composed of a granular aggregate of secondary quartz and felspar. These "eyes" are usually wrapped round by fibrous and ribbon-like laminæ of muscovite. Such granites may be termed **gneissose granites.**

On the other hand, some granites undoubtedly possess a parallel structure which is original and due to fluxional movements prior to consolidation.

DISTRIBUTION OF BRITISH GRANITES.

West of England. Five large masses of granite (granite-porphyry) occur in Devon and Cornwall. These have been respectively designated the Dartmoor, Brown Willy, St. Austell, Carn Menelez and Land's End masses. Besides these there are many smaller exposures. The rocks have a grey colour. They are very handsome, owing to the presence of large porphyritic crystals of felspar, and are largely used as ornamental building-stones.

Midland Counties. Malvern Hill (gneissose granites), Ercal Hill (granophyre), Charnwood Forest (biotite-granite).

Lake District. Three principal masses:—Shap (granite-porphyry), Skiddaw (biotite-granite), and Eskdale (granophyre). The Shap granite is a beautiful rock with fine porphyritic crystals of pink felspar. It is much prized as an ornamental stone.

Cheviot District. Near Staindrop Rigg and Hedgehope (augite-granite).

Wales. St. Davids, and many places in North Wales and Anglesey; *e.g.*, Twt Hill, Ty-mawr, Rhos Hirwain, Ty-Croes, Llanfaelog, Y Foel Fras, Moel Perfedd, Mynydd Mawr (granophyres), and Clynog-fawr (granite-porphyry).

Scotland. In the southern uplands there are three principal masses:—Dalbeattie and Criffel, Cairns Muir of Fleet and New Galloway, and Loch Doon. (In part, hornblende-biotite-granites.)

In the Western Isles of Scotland (Mull and Skye) granites (granophyres) of Tertiary age occur. The Arran rock is a biotite-granite.

Many exposures of granite occur in the Central Highlands; for instance, those of Ben Nevis (hornblende-granite), Ben Vuroch (gneissose granite), Aberdeen (normal granite), and Peterhead (biotite-granite). The Aberdeen and Peterhead granites are extensively quarried for building and ornamental stones. The former is a grey, the latter a red granite.

Ireland. The largest mass of granite in the British Isles is the Mount Leinster mass in the S.E. of Ireland. The stone, which varies considerably in texture and quality, is quarried at Killiney and elsewhere for building and paving purposes. In the N.E. of Ireland there are three principal occurrences:—Mourne Mountains (biotite-granite), Carlingford (granophyre), and Newry. In the N.W. gneissose granites occur in Donegal, Galway and Mayo.

2. THE ELVAN[1] FAMILY.

This family comprises rocks that have the same general composition as granite, but which occur in dykes and veins. In many cases they are doubtless apophyses or tongues sent off from some granite mass into the surrounding slates.

They may be subdivided into:—

Quartz and Felspar Porphyries,
Microgranites,
Felsophyres[2] and Pitchstones.

Quartz-porphyry—consists of porphyritic crystals of quartz and felspar, or of quartz alone, imbedded in a finely crystalline or compact ground-mass composed of the same minerals. In *felspar porphyry* the porphyritic constituent consists of felspar alone.

"The quartz, which may be colourless, white, or smoky, occurs sometimes in bi-pyramidal crystals, but oftener in rounded grains, sinking in size to mere blebs. The felspar is frequently present in the form of large, well-defined crystals, which may be either transparent and colourless, or white, pink, red, or grey; in other varieties the crystals are very minute and can only be discovered by the aid of the lens. They decompose readily under the influence of weather into kaolin,"[3] and the resulting cavities get filled with schorl or chlorite.

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[1] "Elvan" is the Cornish miner's term for certain granitic and porphyritic rocks that occur abundantly in the mining districts of Devon and Cornwall.

[2] This term is selected in preference to "felsite," which is now more generally applied in this country to the acid quartzo-felspathic lavas—the devitrified rhyolites and obsidians.

[3] J. A. Phillips.

Ferro-magnesian minerals are present in small quantity only. In the Cornish porphyries, schorl or black tourmaline is often abundantly present in isolated crystals or stellate groups.

The ground-mass consists of a microcrystalline or cryptocrystalline aggregate of quartz and felspar The cryptocrystalline structure is often spoken of as felsitic. The individual granules of which the "felsitic matter" is composed, are so minute as scarcely to be recognisable even under high powers of magnification. Between crossed nicols such a ground-mass has a characteristically dappled or flecked appearance, produced by the transmission of innumerable mere points of light. Frequently the ground-mass is microcrystalline in the central part of a dyke, and cryptocrystalline or felsitic towards the margin.

In some cases the ground-mass is granophyric; that is to say, the porphyritic grains are imbedded in a base of micropegmatite. Beautiful spherulitic structures are frequently produced in such rocks by a radial arrangement of the alternating lamellæ and fibres of quartz and felspar (*e.g.*, the quartz-porphyries of St. Davids, South Wales; the Armboth dyke in the Lake District; and the Western Isles of Scotland).

Microgranite.—The microgranites are those elvans that possess no porphyritic constituent, and consist of a granitoid but finely crystalline aggregate of quartz and felspar, together with a small amount of muscovite or some ferro-magnesian constituent (see Fig. 35). Small red garnets and fine needle-like prisms of dark schorl are frequent accessories. The rocks are generally of a light colour, varying from white to buff. Veins and dykes of microgranite abound in the neighbourhood of granite, which they also penetrate. The white microgranite, consisting of quartz, felspar, muscovite and garnet, that is so frequently found traversing granite in narrow dykes and veins (Devon and Cornwall, Killiney Hill, near Dublin), is variously known under the names of **eurite, aplite** and **granulite.**[1]

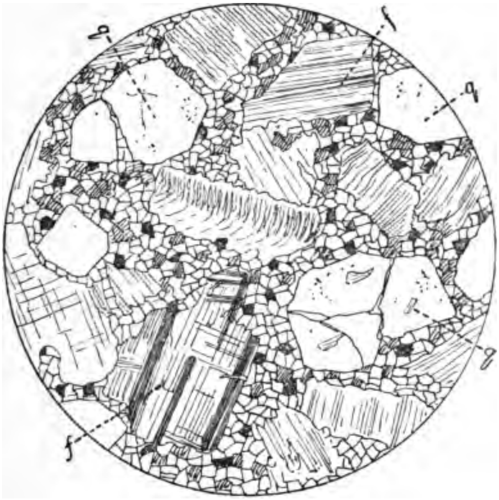

FIG. 35.
Microgranite, under the microscope.
Crystals of Quartz and Felspar in a microcrystalline ground-mass.
q. Quartz. *f.* Felspar.
(*After Fouqué and Lévy.*)

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[1] This is a use of the term totally distinct from the signification attached to it by the French, who apply it to an ordinary muscovite-biotite granite; while the biotite-granites are called by them simply "granite."

Felsophyre or **Pitchstone.**—This is a semi-vitreous rock, having the same chemical composition as granite, and without doubt produced by a more rapid consolidation of the granite-magma, when injected into narrow fissures or between bedding planes. It is characterized by a resinous appearance, conchoidal fracture and streaky fluidal structure.

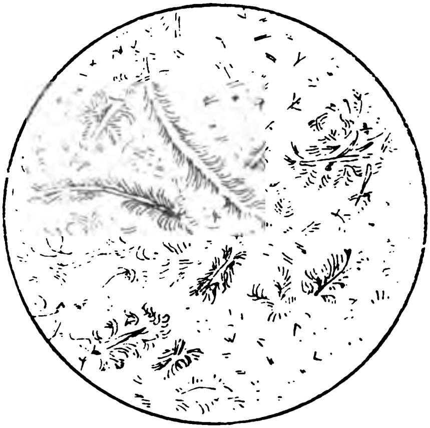

FIG. 36.

Pitchstone of Arran, under the microscope, showing minute microlites of Hornblende aggregated to feathery forms, in a glassy base.
(*After Teall.*)

The colour is usually a dark-green, but sometimes black or red. Under the microscope the glass is seen to contain numerous crystallites and microlites, often arranged in beautiful stellate and feathery groups, or resembling fern-growths (see Fig. 36). Spherulitic structures are not infrequent.[1] Imbedded in the glassy ground-mass are often porphyritic crystals of quartz, orthoclase, mica, hornblende and augite.

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[1] The **Pyromerides** of the French or **Kugelporphyre** of the Germans are spherulitic rocks of this type.

With regard to chemical composition, they differ from the granites and microgranites only by containing some 6–8% of water.

The well-known pitchstones of Arran constitute beautiful examples of this rock. They occur there in dykes and intrusive sheets. Other occurrences are Scuir of Eigg, and Newry in Ireland.

3. THE RHYOLITE FAMILY.

The rhyolites[1] are the volcanic equivalents of the plutonic granites and intrusive elvans. They are highly acid rocks, containing, in most cases, free silica in the form of quartz. In consequence of their having been poured out as subaerial or submarine lavas, they present marked fluidal, spherulitic and perlitic structures. Occasionally the rocks are compact, but more usually they have a porphyritic structure. The porphyritic constituents are quartz and felspar, imbedded in a light-coloured trachytic ground-mass, which is mainly composed of microlites of felspar. Prisms of augite and hornblende, plates of biotite and granules of magnetite also occur. A glassy base is present in variable proportion.

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[1] The name *rhyolite* was given to these rocks on account of the fluidal structure frequently shown by them. They have also been termed **Quartz-trachytes**, and again **Liparites**, this designation having been given them on account of their occurrence in the Lipari Islands. A crystalline and granitoid variety of rhyolite has been described under the name of **Nevadite** by Richthofen.

Accessory minerals are magnetite, tridymite, apatite, cordierite, garnet, sphene and allanite.

The grains of quartz are sometimes bi-pyramidal, but oftener without definite shape. Though usually pellucid and colourless, they have frequently a dark-coloured or smoky hue. In some rhyolites the conditions of eruption have been such as to prevent the separation of quartz; but the high percentage of silica facilitates the correct diagnosis of such rocks.

The felspar is usually sanidine, a glassy variety of orthoclase. It occurs frequently in large tabular crystals, which are glassy, clear and much fissured; but also in smaller and less regular grains. In addition to the orthoclase there is often present a striped (triclinic) felspar. This is sometimes oligoclase, but more frequently a soda-felspar (albite, soda-microcline or anorthoclase). In some rhyolites (Hungary) the sole porphyritic constituent is a soda-felspar, having the same glassy habit as the potash-felspar (sanidine), and consequently liable to be mistaken for it. According to the predominance of potash-felspar or soda-felspar, the rhyolites may be divided into **potash-rhyolite** and **soda-rhyolite.**[1]

Fluxion-structure is often shown in the ground-mass by the beautiful wavy lines of flow which sweep round the larger imbedded grains. The same structure is also occasionally brought out under the microscope by the strict parallelism of the felspar-microlites.

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[1] The rhyolites containing anorthoclase (soda-potash felspar) are termed **pantellerites.**

Felsite.[1]—The identity of many felsites with the rhyolites has been demonstrated by the researches of Rutley and Allport.[2] These rocks, which consist of a cryptocrystalline aggregate of quartz and felspar (felsitic matter), in which porphyritic crystals of quartz and felspar are often imbedded, were found to possess traces of perlitic, spherulitic and fluidal structures (see Fig. 31). These structures, being characteristic of rocks that have consolidated in a vitreous or semi-vitreous condition, at once indicated the true nature of the felsites. They are, in fact, ancient flows of rhyolitic lava that have subsequently acquired a cryptocrystalline structure by a gradual process of devitrification. Like the rhyolites, they contain porphyritic crystals of both unstriped and striped felspar, and their chemical composition shows that they may be divided into **potash-felsite** and **soda-felsite.**[3]

In association with tuffs and breccias, which were doubtless formed by the same volcanic activity, the felsites are found interbedded with sedimentary strata. Occasionally they occur in dykes; but these, no doubt, were originally in connection with some volcanic vent.

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[1] Term introduced by Gerhard (1814). Synonymous terms are **eurite,** introduced by Daubuisson (1819); and **petrosilex,** introduced by Brongniart. The revival of the word "eurite" has been recently advocated by Cole and Jennings.

[2] It was, however, Ward who first indicated the relation of the Welsh felsites to modern volcanic rocks (rhyolites).

[3] Felsites, rich in alkalies, especially soda, are termed **Keratophyres** by German petrologists.

DISTRIBUTION IN THE BRITISH ISLES.

Glassy rhyolites that have not undergone devitrification are not known to occur in the British Isles. The nearest approach to them is afforded by the tridymite-bearing rhyolite of Tardree, Co. Antrim.

Felsites, among which is a beautiful spherulitic variety, occur near Wellington, in Shropshire. They are said to be of pre-Cambrian age. Other occurrences are Malvern Hills, Charnwood Forest, and near Nuneaton. Several localities for felsite are known in *South Wales;* for example, at St. Davids, Ramsey I., Skomer I. In *North Wales,* felsites of Lower Silurian (Ordovician) age abound: they are frequently nodular, and often present spherulitic and perlitic structures.

In the *Lake District,* numerous occurrences have been noted: between Shap Wells and Stockdale, (nodular felsites); in Long Sleddale; near Grizedale Tarn; and in the Copper Mine Valley.

Western Isles of Scotland. Arran, Mull, Skye.

Ireland. Lower Silurian felsites, similar to those of Wales, occur in the S.E. of Ireland (counties Wicklow, Wexford and Waterford). In Co. Kerry they are of Old Red Sandstone age.

Table showing the mutual relations of the members of the acid group.

INTRUSIVE.			VOLCANIC.	
Deep-seated (plutonic) masses.	*Dykes, and intrusive sheets.*		*Fresh.*	*Altered, etc.*
Granites Granitites Granite-porphyries Granophyres	Quartz porphyries Felspar porphyries Microgranites Granophyres	Elvans.	Rhyolites Obsidian	Felsites
	Felsophyres Pitchstones			

4. THE SYENITE AND DIORITE FAMILY.

The syenites and diorites are plutonic holocrystalline rocks, having a granitoid structure and differing from granite only by the absence of quartz or its presence in small quantity.

They may be divided into—

Syenite[1] = orthoclase + a ferro-magnesian mineral.

Elæolite-syenite = orthoclase + a ferro-magnesian mineral + elæolite.

Diorite[2] = plagioclase + a ferro-magnesian constituent.

The syenites are composed of orthoclase and a member of the ferro-magnesian group. According to the nature of the latter we have **hornblende-syenite** (or syenite proper), **augite-syenite,** or **mica-syenite.**

A small quantity of quartz is sometimes present, and must then be regarded as accessory. Other accessory minerals are oligoclase, sphene, zircon, epidote, apatite and ilmenite.

The hornblende, which, with rare exceptions, is a green variety, may be recognised by its pronounced pleochroism, its well-marked cleavage, its prism angle of 124°, small extinction angle, etc. The augite is more variable in character: sometimes it is almost colourless or pale-green; at other times it partakes more of the nature of diallage, having then a violet-brown tint. The mica is always a brown biotite. It is very liable to chloritization, turning green in the first stage of the process. Muscovite is never present unless as a secondary constituent.

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[1] The term *syenite* was applied by Pliny to a rock occurring at Syene (Assouan), in Egypt. This rock is a hornblende-biotite-granite. Werner introduced the term in the sense used above.

[2] Term introduced by Haüy. The diorites differ from the hornblende-gabbros and hornblende-diabases by their greater acidity and by their mode of occurrence. They constitute a link between the basic rocks and the granites, just as the andesites do between the basalts and the rhyolites.

The average chemical composition of the syenites is :—$SiO_2 = 58{\cdot}4\%$, $Al_2O_3 = 19{\cdot}2\%$, $FeO = 8{\cdot}3\%$, $CaO = 5{\cdot}6\%$, $MgO = 2{\cdot}9\%$, $K_2O = 3{\cdot}2\%$, $Na_2O = 2{\cdot}4\%$. Sp. G. $= 2{\cdot}75 - 2{\cdot}9$ (von Lasaulx).

True syenites do not appear to occur in this country, unless some isolated occurrences in N.W. Carnarvonshire (Llanfaglen and Glan-y-mor) be regarded as such. The celebrated occurrence in the Plauenscher Grund, near Dresden, may, however, be taken as a type.

Elæolite-syenite—is characterized by the presence of an altered variety of nepheline (elæolite), which resembles quartz, but may be distinguished from this mineral by its characteristic greasy lustre. With elæolite is often associated green or blue sodalite. Zircon, sphene, allanite and other rarer minerals, often occur as accessory constituents. Ferro-magnesian minerals (pyroxene, amphibole and biotite) also occur in small proportions.

Elæolite-syenites do not occur in this country. The best known localities are Löven and Brevig in Southern Norway (**zircon-syenite**, in part), Ditro in Transylvania (**ditroite**, a variety containing sodalite), Foya Hills in Southern Portugal (**foyaite**, a hornblendic variety), the provinces of Rio de Janeiro and Minas-Geraes in Brazil (**foyaite**), Ilmen Mountains near Miask (**miascite**, a micaceous variety), Kangerdluarsuk, on the S. coast of Greenland (with arfvedsonite and eudialyte).

Diorite.—The diorites differ from the syenites in having as the dominant felspar plagioclase (lime-soda felspar), instead of orthoclase (potash-felspar). In other respects they closely resemble them. Like the syenites, the diorites have a holocrystalline granitoid structure; although the latter are, as a rule, much finer in grain. The ferro-magnesian constituent is usually green hornblende in crystals, grains, or needles (in **needle-diorite**); but brown biotite, pale green or colourless augite and enstatite also occur, constituting the varieties,—**mica-diorite, augite-diorite** and **enstatite-diorite.** Among accessory minerals the iron-ores (magnetite and ilmenite), apatite, sphene and zircon are the most frequent. Secondary minerals are represented by chlorite, epidote, limonite and calcite. Quartz occurs sometimes as a mineral of secondary origin, at other times as an original constituent. Diorites that contain much quartz are termed **quartz-diorite**; but the diorites are rarely without some quartz. **Tonalite** is a quartz-mica-diorite. **Epidiorite** is the name given to a plagioclase-hornblende rock in which the hornblende is derived from augite. The epidiorites, however, belong properly to a more basic class, the rocks from which they are derived being gabbros and dolerites.

Spheroidal structure, similar to that described when dealing with the granites, is well developed in the **ball-diorite** or **napoleonite** of Corsica, where the spheroids consist of hornblende and felspar, and show a well-developed radial and concentric arrangement.

DISTRIBUTION IN THE BRITISH ISLES.

England. Diorites occur in the Charnwood Forest (Groby, Markfield, Cliff Hill, Bowdon Castle, Bradgate, and Hammer Cliff), in the Malvern Hills, in the neighbourhood of Nuneaton in Warwickshire, in Cornwall (as veins in the gabbro of Pen Voose), and in the Lake District. Typical diorites occur in the *Channel Islands:* Guernsey and Jersey. In *Wales,* a quartz-diorite has been described as occurring in the ridge S. of Haverford-west and at Talbenny, in Pembrokeshire. A fine example of enstatite-diorite occurs at Penmaenmawr in Carnarvonshire, and is quarried for road-metal. Diorites occur in many places in *Scotland.* They have been described in Arran, in Perthshire (Glen Tilt), and as intrusive sheets in the limestone and quartzites of the Assynt district. Excellent examples of quartz-diorite and tonalite exist as intrusive masses in the Ordovician rocks of County Wicklow, Ireland.

5. THE MICA-TRAP OR LAMPROPHYRE[1] FAMILY.

This family corresponds to the elvans in the acid group. It comprises rocks of intermediate composition which occur always in the form of narrow dykes or veins, unaccompanied by tuffs. They are fine-grained, dark-coloured rocks, usually much altered and inclined to spheroidal weathering. Characteristic for them is the abundant presence of brown mica, which also takes the place of felspar as the porphyritic constituent. Rosenbusch divides the lamprophyres into (1) those of a syenitic, and (2) those of a dioritic type. The syenitic mica-traps are composed essentially of orthoclase and biotite, and are termed **minette.**[1] The dioritic lamprophyres are composed of plagioclase and biotite, and are termed **kersantite.**[2]

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[1] The name *Lamprophyre* was introduced by Gümbe in describing the mica-traps of the Fichtelgebirge, and adopted by Rosenbusch as a general and comprehensive name for the members of this family.

In both rocks the mica occurs in lustrous scales and plates of a dark brown colour. Under the microscope the plates are of a paler hue and have ragged edges. In convergent light the mineral is seen to be biaxial, but with a small optic axial angle. By alteration it passes into chlorite, thence into limonite, quartz and calcite (or dolomite). Accessory minerals are apatite, iron-ores and quartz (both original and secondary). Calcite and other carbonates (dolomite, magnesite) are rarely absent; they occur in plates or scattered dust.

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[1] The term **minette** was introduced by Voltz in 1828. A second type of syenitic lamprophyre, containing hornblende instead of mica, is termed **vogesite** by Rosenbusch (*Physiographie*, p. 314).

[2] The term "**kersanton**" is used in a more general sense: it is used by Barrois so as to include kersantites and mica-porphyrites, the former being *granular* mica-plagioclase rocks, the latter containing *porphyritic* felspars. Another type of dioritic lamprophyre, consisting of plagioclase and hornblende, is termed **camptonite** by Rosenbusch (*Physiographie*, p. 328).

DISTRIBUTION IN THE BRITISH ISLES.

Mica-traps occur in *N. W. England* at the following localities: Cross Haw Beck; Railway cutting, Windermere; Kendal road; railway, Docker Garth; S. of Haygarth; Helm Gill; Taith's Gill; in the Rawthey; Backside Beck (all minettes); and at Holbeck Gill; Uldale Head; Wattle Gill; Westerdale; Thornton Beck, near Ingleton; S. E. of Skirwith, near Ingleton; and in Ingleton Beck (kersantites). In *Cornwall*, at Trelissick Creek near Falmouth (minette), and between Rosecreage Beacon and Watergate Bay on the W. coast (kersantite). Excellent mica-traps occur in *Devonshire*, at Rose Ash and other localities. In the *Channel Islands*, at Moulin Huet and Bec du Nez in Guernsey (kersantites). In *Scotland* mica-traps occur among the Silurian rocks of the Southern Uplands, also in the Highlands.

6. THE TRACHYTE AND ANDESITE FAMILY.

The name *trachyte* was originally applied to all volcanic lavas which, owing to their vesicular texture,[1] are rough to the touch. The use of the term, however, has been gradually limited. First, it was restricted to rocks of intermediate composition; and then these have been found, in the light of modern research, to be capable of further subdivision according to the nature of the dominant felspar. This mineral, which occurs in these rocks in glassy porphyritic crystals, is either the monoclinic potash variety (sanidine) or a soda-lime plagioclase (oligoclase, andesine). The term trachyte is now applied solely to the former; while the latter, on account of their abundant occurrence in the Andes of S. America, are termed *andesites*.

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[1] Gr. τραχύς, rough.

Trachyte.—The trachytes are the volcanic equivalents of the syenites. They are light-coloured, often porous rocks, consisting mainly of felspar. Ferromagnesian minerals occur only in small proportion. The porphyritic felspar—sanidine—forms either tabular crystals, twinned on the Carlsbad type, or irregular grains. In the ground-mass, however, the felspar appears in long needles and microlites, which are unstriated and doubtless consist also of orthoclase. They often exhibit a parallel arrangement, due to fluidal movements in the mass. Interstitial matter, when present, is usually felsitic, a true glassy base being rare. The ferro-magnesian minerals are brown mica, green amphibole, colourless or pale green pyroxene (malacolite), and a pleochroic rhombic pyroxene (hypersthene, bronzite). According to the nature of the dominant species, the trachytes may be divided into **mica-trachyte, amphibole-trachyte,** and **pyroxene-trachyte.**

Accessory minerals are abundant: iron-ores, zircon, apatite, sphene, cordierite, haüyne and nosean. Quartz is occasionally present in small quantity, forming thus a passage to the rhyolites. On the other hand, some trachytes have had their silica-percentage increased, subsequently to consolidation, by hydrothermal impregnation with secondary silica (chalcedony, hyalite, opal, etc.).

Trachytes occur in flows, dome-shaped[1] masses, and dykes, in numerous volcanic districts: Auvergne, Siebengebirge, Henry Mountains in America, etc.; but they have not been described in this country.[2]

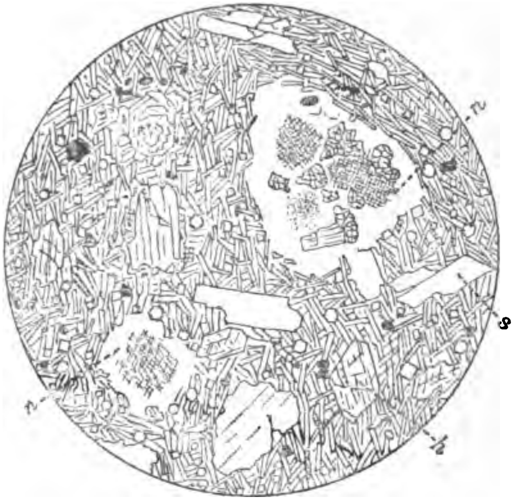

FIG. 37.
Phonolite, under the microscope.
n. Nosean. *s.* Sanidine. *h.* Hornblende.
The microlites are Sanidine, and the square and hexagonal sections, Nepheline. (*After Fouqué and Lévy.*)

Phonolite,[3] or **nepheline-trachyte** is the volcanic equivalent of elæolite-syenite. It is a trachytic rock composed essentially of sanidine, nepheline and a ferro-magnesian constituent (see Fig. 37). Sometimes the place of the nepheline is taken by leucite, and then the rock is termed **leucite-trachyte** or **leucite-phonolite.** **Leucitophyre** is the name given to a rock containing both nepheline and leucite together with sanidine. Associated with the nepheline or leucite are sodalite, nosean and haüyne. The ferro-magnesian constituent is generally a green augite, sometimes a soda variety of that mineral (aegirine). Brown mica and hornblende occur as accessory constituents. Other accessories are apatite, iron-ore (magnetite), sphene and melanite (black garnet). Natrolite and other zeolitic minerals result from the alteration of the nepheline.

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[1] Hence the term **domite** applied to the trachytes of the Auvergne.

[2] Prof. Judd informs me, however, that excellent sanidine-trachytes exist among the Old Red Sandstone "porphyrites" of Haddington.

[3] Name introduced by Klaproth. Gr. *phonos,* a sound.

The phonolites are usually very compact rocks of a greyish-green colour, with a spotted appearance. They ring under the hammer, and hence have been termed **clinkstone.**[1] A platy and spheroidal mode of weathering is a characteristic feature of these rocks, the decomposing rock having a concentric shelly structure like that of an onion.

The only known occurrence of phonolite in the British Isles is that of the Wolf Rock, off the coast of Cornwall.

The **andesites** are dark-coloured, compact or vesicular, semi-vitreous volcanic rocks occurring in lava-flows and dykes. They are composed essentially of a glassy plagioclase felspar and a ferro-magnesian constituent together with a glassy base; and may be regarded as the volcanic equivalents of the plutonic diorites. According to the nature of the ferro-magnesian constituent, they may be divided into **hornblende-andesite**, **biotite-andesite** and **pyroxene (augite and hypersthene)-andesite**; and the intermediate varieties produced by the various combination of these minerals. (See Figs. 38 and 39.) The hornblende is the common brown variety, occurring in well-formed lozenge-shaped crystals, which often have a dark border, due to the corrosive action of the molten magma in which they floated when first formed. The monoclinic augite is of a pale brown colour and is non-pleochroic. The hypersthene is pleochroic, in pale green and reddish tints. Both occur in well-formed crystals, giving square sections

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[1] Ger. *Klinkstein.*

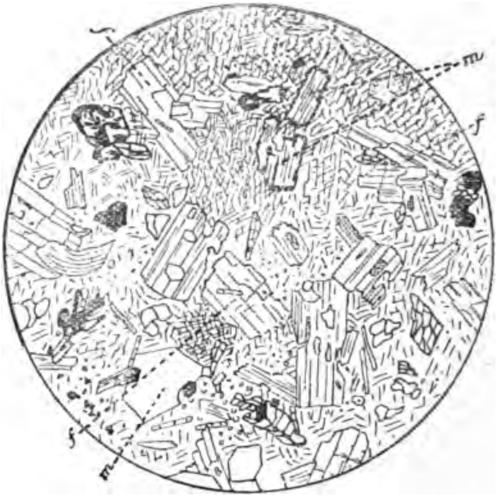

FIG. 38.
Andesite (Mica-andesite), under the microscope.
Porphyritic crystals of Plagioclase Felspar (*f*) and Mica (*m*) imbedded in microlitic ground-mass. (*After Fouqué and Lévy.*)

with truncated corners. The felspar occurs in good-sized crystals, producing a marked porphyritic structure. In its glassy character it resembles sanidine, but it is distinguished therefrom by its twin-striation. Accessory minerals are magnetite, apatite, garnet, sphene, olivine, allanite and cordierite. Quartz is sometimes present. When this mineral forms a non-negligible proportion of the mass, the rock is termed **quartz-andesite** or **dacite.** Some rocks, however, that from chemical analysis might be considered as dacites, owe their acidity to secondary impregnation, by hydrothermal agencies (warm springs contain-

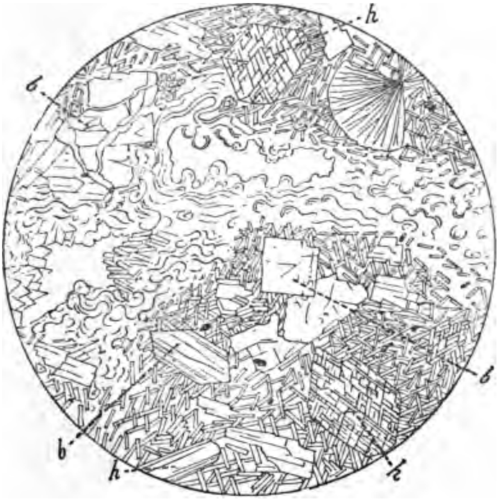

Fig. 39.

Hornblende-Andesite, under the microscope.

Porphyritic crystals of Plagioclase Felspar (*b*) and Hornblende (*h*) in a microlitic ground-mass. (*After Fouqué and Lévy*).

ing dissolved silica), with chalcedonic and opaline silica. The ground-mass of the andesites is usually microlitic, being composed of needles of felspar and an abundant glassy base. The latter is generally of a pale brown colour, and either clear or partially devitrified. By an increase in the proportion of this base, the rocks gradually pass into true andesitic glasses.

Tholeiite is the name given to a variety of andesite in which the felspar occurs in lath-shaped crystals, forming a mesh which is filled up by augite in aggregates of small granules, magnetite and interstitial matter.

The **porphyrites** are altered andesites.[1] In them the felspar, instead of being fresh and glassy, is kaolinized and turbid, the augite is partially or completely converted into chlorite, the hypersthene into the fibrous bastite, and the magnetite into red oxide of iron. The vitreous character of the andesites gives place, in the porphyrites, to a dull stony appearance due to the devitrification of the glassy base; and the rocks are tinged red by much disseminated oxide of iron, or green by diffused chlorite.

The famous "*porfido rosso*" and "*porfido verde*" of the ancients belong to this category. The green porphyry of Lambay Island on the E. Coast of Ireland, and of the Lake District resembles the *porfido verde.*

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[1] Prof. Judd has recently applied the almost forgotten term **propylite** to such andesites as have been altered by solfataric action.

DISTRIBUTION OF ANDESITES AND PORPHYRITES IN THE BRITISH ISLES.

Andesites and porphyrites occur as lavas accompanied by tuffs among the Old Red Sandstone rocks of the *Cheviot district* (*e.g.*, the enstatite-andesite of Yetholm,[1] and Windy Haugh on the Coquet). They occur abundantly in the *Lake District* (*e.g.*, near Keswick, at Falcon Crag, Brown Knotts and Eycott Hill; in the Breidden Hills of Shropshire and Montgomeryshire; and in the Triassic rocks of *Devonshire* (in the neighbourhood of Exeter). In the Lleyn peninsula of *Wales:* Carn Boduan; Penmaen Castle, W. of Pwllheli; Y Foel Fawr, 1½m. W. of Llanbedrog. In *Scotland* they were abundantly erupted in lower Old Red Sandstone and Carboniferous times: Garlton Hills in Haddingtonshire, Pentlands, Ochils, Isle of Bute, etc. Some of the North-of-England and Scotch dykes are typical Tholeiites (Hett dyke, Tynemouth dyke and Hebburn dyke).

Table showing the Relations of the Members of the Intermediate Group to one another.

INTRUSIVE.		VOLCANIC.	
Deep-seated (plutonic) masses.	*Dykes.*	*Fresh.*	*Altered.*
Syenites	Minettes	Trachytes	Some Felsites (?)
Elæolite (or Nepheline)-syenites		Phonolites or Nepheline-trachytes	
Diorites	Kersantites	Andesites	Porphyrites.
		Tephrites or Nepheline-andesites	

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[1] Where the church is built of it.

7. THE GABBRO[1] FAMILY.

The members of this family, which comprises the plutonic representatives of the basic group, are granitoid, often coarsely crystalline, aggregates of a plagioclase felspar and a ferro-magnesian constituent. The variability in regard to the ferro-magnesian constituent permits of the following varieties being distinguished :

Gabbro proper (plagioclase + augite).
Hornblende-gabbro[2] (plagioclase + augite + hornblende).
Olivine-gabbro (same + olivine).
Norite or **hypersthene-gabbro**[3] (plagioclase + rhombic pyroxene).
Olivine-norite (same + olivine).
Troctolite (plagioclase + olivine).
Pyroxene-granulite (plagioclase + monoclinic and rhombic pyroxenes + garnet).

The felspar of these rocks occurs in allotriomorphic grains, showing well-marked twin-striation. Chemical composition and optical properties (*e.g.*, large extinction angles between crossed nicols), show that it belongs to the anorthite end of the lime-soda series. Though often perfectly fresh, it alters under the influence of surface agencies into an opaque white substance known as saussurite. Submitted to microscopic examination, saussurite resolves itself into a confused and intimately aggregated mass of granules and fibres of several minerals, chief among which are zoisite, epidote and secondary felspar (albite), the last of water-clear and glassy habit.

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[1] The term Gabbro is now used in a sense differing from its original application ; it was first given to an Italian serpentine containing diallage. A synonymous term is **euphotide**, used by the French.

[2] This type forms a passage to the more acid augite-diorites.

[3] Synonyms for this type are **hypersthenite, hyperite** and **Schillerfels.**

The hornblende, when original, is sometimes a brown, sometimes a green variety. Secondary hornblende (actinolite, smaragdite, uralite), derived from the pyroxene, is also not uncommon, especially in those rocks that have suffered mechanical disturbance. The augite is most frequently the laminated variety termed diallage, cleavage surfaces of which have a marked metallic or pearly lustre. Under the microscope sections oblique to the lamination appear finely striated. The hypersthene is characterized by its pleochroism; and also presents a well-marked coppery lustre due to reflection from numerous platy and rod-like inclusions arranged along parallel planes. The olivine when fresh is colourless. It is, however, often stained with limonite, and crowded with rods and granules of magnetite.

Minerals accessory to the gabbros are dark mica, quartz, apatite, ilmenite, rutile and green and brown spinels (pleonaste, picotite, chromite).

The structure of these rocks is essentially holocrystalline and granitoid, the constituent grains being allotriomorphic. Sometimes, especially when passing over into dolerites, the rocks show a tendency towards ophitic structure. In size the grains vary considerably, so that both coarse and fine textures occur.

Chem. comp. varies from 48 to 54·6% SiO_2; 10·4 – 28·9% Al_2O_3; 4·8 – 15·8% FeO, Fe_2O_3; 9 – 18% CaO, MgO; 0·01 – 2·69% K_2O; 0·5 – 6·2% Na_2O. Sp. G. = 2·9 – 3·02 (von Lasaulx).

Troctolite[1] is a variety of gabbro consisting almost entirely of plagioclase and olivine. This rock derives its name from its spotted appearance, due to the olivine grains being black with included magnetite.

Pyroxene-granulite[2] is the name given to certain rocks of dubious origin (but probably plutonic and therefore belonging to this category) that occur in the granulitic area of Saxony, in Sutherlandshire, Madagascar, and the United States. They consist essentially of plagioclase felspar, hornblende, both monoclinic and rhombic pyroxene and garnet. The rocks are characterized by the freshness of the minerals and by a finely granular (or "granulitic") structure.

DISTRIBUTION IN THE BRITISH ISLES.

England. Lizard district of Cornwall (olivine-gabbro); Carrock Fell in the Lake District.

Wales. Anglesey, and Sarn district in the Lleyn peninsula.

Scotland. Western Isles—Mull, Skye, Rum (olivine-gabbro, troctolite); Portsoy in Banffshire; Parish of Belhelvie in Aberdeenshire (troctolite); Carrick district of Ayrshire; Sutherlandshire (pyroxene-granulite).

Ireland. Carlingford district.

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[1] Trout-stone (Ger. *Forellenstein*).

[2] Name given by Lehmann. Syn. **Trap-granulite** (Naumann).

8. THE DOLERITE FAMILY.

The Dolerite family consists of dark green basic rocks occurring in the form of intrusive bosses, sheets, laccolites and dykes, or constituting the more deeply seated portions of basaltic lava-flows. When fresh, they are termed dolerites; when altered, diabases. The time-honoured word "**greenstone**"[1] was formerly used to cover these rocks, and is still so used by some field-geologists. They are essentially composed of plagioclase felspar and a ferro-magnesian constituent, the variation in the nature of the latter furnishing the following varieties:

Dolerite (and **diabase**). . plagioclase + augite.
Mica-dolerite, plagioclase + augite + brown mica.
Hornblende-dolerite (or **proterobase**), plagioclase + augite + original hornblende.
Enstatite-dolerite, plagioclase + augite + enstatite.
Olivine-dolerite, plagioclase + augite + olivine.
Epidiorite, plagioclase + secondary hornblende.
Leucophyre . . . chiefly plagioclase.

The plagioclase (labradorite or anorthite) may be quite fresh or it may be much decomposed, altering then into an aggregate of minute granules of epidote, calcite and, occasionally, quartz. In thin section the augite is usually of a pale violet-brown tint. It mostly occurs in large ophitic masses, enclosing lath-shaped crystals and microlites of felspar. In the diabases the augite is partially, sometimes even completely, replaced by a scaly and fibrous aggregate ot some chloritic mineral. It is the presence of this mineral in greater or less abundance that imparts to the diabases their characteristic green colour.

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[1] De la Beche, in his report on the geology of Cornwall, Devon and West Somerset, defines (p. 27) "Greenstone" as a combination of hornblende and felspar. Microscopic examination, however, has shown that the ferro-magnesian constituent of these rocks is essentially augite, the hornblende being mainly of secondary origin.

The hornblende of the proterobases is the common brown variety. In the epidiorites however, it is of a pale green colour (uralite, actinolite, smaragdite), and is produced by paramorphism of the augite.

The olivine of the olivine-bearing dolerites is rarely quite fresh, being stained brown with limonite, blackened with magnetite dust, or completely replaced by serpentine or calcite.

Other minerals, more or less abundantly present, are the iron-ores, magnetite and ilmenite, the latter giving rise, when altered, to leucoxene (an amorphous variety of sphene), and apatite in six-sided needles. Quartz, calcite, epidote, chlorite and serpentine are common secondary minerals.

The structure of the dolerites is characteristically ophitic; but, in some cases, a granular, in others, a porphyritic structure prevails. Interstitial glassy matter, or its devitrified equivalent, is rarely present, most dolerites being holocrystalline. The very close-grained and compact diabases are known as **aphanites.** The dolerites occur in dykes, intrusive sheets, and laccolites. Their intrusive character is especially shown by their contact phenomena: baking or "porcellanization" of shales: formation of banded and spotted rocks (desmoisites and spilosites) and of hornstone-like rocks rich in alkalies (adinole). The more deeply-seated parts of massive lava-flows are often doleritic in texture.

DISTRIBUTION OF BRITISH DOLERITES.

England. Diabasic rocks are intrusive in the Devonian and Carboniferous rocks of Devon and Cornwall. They are also associated with Carboniferous rocks in the Midland Counties—Leicestershire, Gloucestershire and Shropshire (*e.g.*, Pouk Hill and Rowley Rag). In the Lake District they are represented, but not well developed (Castle Head near Keswick; Wythorp Fells; Swirrel Edge, near the summit of Helvellyn; and Longstrath in Borrowdale).

Mica-diabases occur at Stanner and Hanter Hill, near Old Radnor, and at Saltash near Plymouth. Enstatite-diabases have been described in the Breidden Hills of Shropshire. Some of the North-of-England dykes are dolerites, *e.g.*, the Whin Sill, which is an enstatite-dolerite.

In *Wales and S.E. Ireland* they are abundant among Ordovician rocks. In the Sarn district of Wales (Lleyn peninsula), hornblende-diabases also occur.

In *Scotland* diabasic rocks,—partly altered to epidiorites and hornblende and chlorite schists,—are abundantly associated with the gneisses and crystalline schists of the Highlands (*e.g.*, the Scourie dyke, described by Mr. Teall). Carboniferous diabases and dolerites occur in the basin of the Firth of Forth (*e.g.*, Salisbury Craigs, Dalmahoy Hill, Ratho, etc). Dolerites of Tertiary age are magnificently developed in the N.E. of Ireland and in the Western Isles of Scotland (Antrim, Mull, Skye, Arran). They are mostly olivine-bearing, and graduate on the one hand into gabbros, and on the other, into basalts.

9. THE BASALT[1] FAMILY.

The basalts are dark-coloured lavas of basic composition and high specific gravity, representing the extrusive or volcanic type of the gabbros and dolerites. When altered or decomposed, they are often termed **melaphyre.**[2] They are characterized by their black or reddish colour and finely crystalline, to compact, texture. Microscopic examination shows them to be composed essentially of plagioclase (labradorite or anorthite) and augite. When olivine is present, the rock is termed olivine-basalt (see Fig. 40). In addition to the augite there are often present larger crystals, or partially fused fragments of brown augite and hornblende (see Fig. 41). Replacing the felspar, or in addition to it, some basalts contain members of the nepheline group (nepheline, leucite, melilite, haüyne, nosean).

---

[1] The word "basalt" is one of the oldest in petrography. It is said to be derived from the Ethiopian word "basal," signifying an iron-bearing stone. According to Pliny, basalt was first brought from the country of the Ethiopians.

[2] Word introduced by A. Brongniart, and since used with various significations. Rosenbusch applied it to Pre-Tertiary basalts. It is here applied to all altered basalts, without regard to their age.

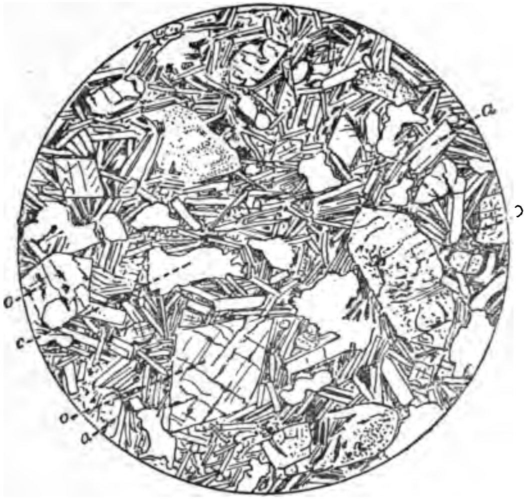

FIG. 40.—Olivine-Basalt, under the microscope.
Porphyritic crystals of Olivine (*o*) and smaller ones of Augite (*a*) imbedded in a microlitic ground-mass. The clear spaces (*c*) are cavities.
(After Fouqué and Lévy.)

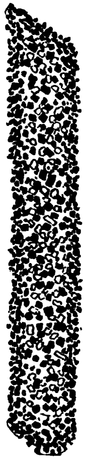

FIG. 41.—Crystal of Fused Hornblende. *(After Hatch.)*

Adopting a mineralogical classification, the different types of basalt may be summarized thus :—

1. Felspar-basalts
    - *a.* **basalt** proper = plagioclase + augite.
    - *b.* **olivine-basalt** = „ + „ + olivine.
    - *c.* **hornblende** (or **mica**) **-basalt** = „ + „ + hornblende (or mica).
2. Felspar -nepheline / -leucite -basalts
    - **tephrite**[1] = plagioclase + nepheline or leucite + augite.
    - **basanite** = plagioclase + nepheline or leucite + augite + olivine.
3. Basalts without felspar
    - **nepheline-basalt**[2] = nepheline + augite.
    - **leucite-basalt** = leucite + augite.
    - **melilite-basalt**[3] = melilite + augite.

---

[1] Rosenbusch (*Physiographie*, p. 248) proposes the name **theralite** for the plutonic representatives of the plagioclase-nepheline rocks; the teschenites, which were formerly supposed to consist of these minerals, having been shown to contain no nepheline.

[2] Rosenbusch (*Ibid.*, p. 290) calls these rocks **nephelinite** and **leucitite** when they are free from olivine, but nepheline-basalt and leucite-basalt when they contain that mineral.

[3] Rosenbusch uses the word **alnöite** for a subdivision of the melilite-basalts (*Ibid.*, p. 805).

Accessory minerals present in the basalts are magnetic iron-ore, in black opaque grains; apatite, in colourless needles; zircon, in conspicuous red grains; and haüyne and nosean (in the nepheline and leucite-bearing varieties). Isolated and much-corroded quartz grains occur; but it is an open question whether they are indigenous to the basalt or have been caught up during its eruption. Chlorite, calcite and epidote, either disseminated or filling amygdaloidal cavities, occur abundantly in the melaphyres, or altered basalts. The chlorite is derived mainly from the decomposition of the augite; the calcite and epidote, from the felspar; while the olivines are mostly entirely replaced by serpentine, limonite, magnetite, or carbonates of lime and magnesia. Zeolites (natrolite, phillipsite, scolecite) and agates are frequently the infilling material of the amygdules of the melaphyres and basalts.

The average chemical composition of the basalts is as follows:—

$SiO_2 = 43\%$; $Al_2O_3 = 14\%$; $Fe_2O_3, FeO = 15{\cdot}3\%$; $CaO = 12{\cdot}1\%$; $MgO = 9{\cdot}1\%$; $K_2O = 1{\cdot}3\%$; $Na_2O = 3{\cdot}9\%$; $H_2O = 1{\cdot}3\%$. Sp. G. = 2·8–3·0 [von Lasaulx].

The tephrites[1] and basanites[2] are the plagioclase-nepheline (and leucite) rocks corresponding to the phonolites (or orthoclase-nepheline rocks). In the nepheline, leucite and melilite basalts, however, felspar is not present as an essential constituent.

---

[1] Name introduced by De la Méthérie and Cordier for the olivine-free plagioclase-nepheline basalts.

[2] Name introduced by A. Brongniart for the olivine-bearing variety.

The nepheline is sometimes present in recognisable six-sided crystals; oftener, however, in small disseminated granules, then only to be detected by

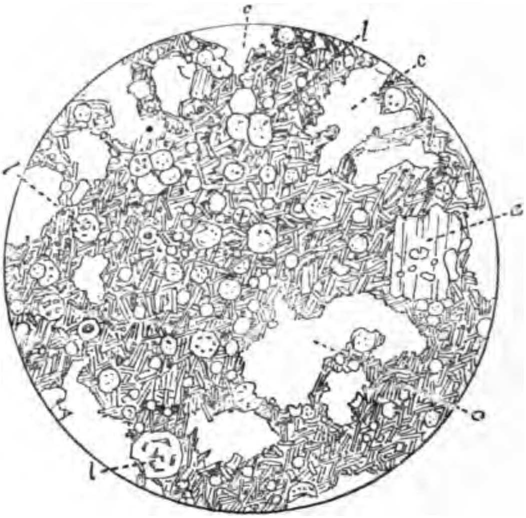

FIG. 42.

Leucite-Tephrite of Vesuvius, under the microscope. Crystals of Leucite (*l*) and Augite (*a*) imbedded in a microlitic ground-mass. The irregular clear spaces (*c*) are cavities. (*After Fouqué and Lévy*)

chemical tests. Leucite, on the other hand, is easily known by its characteristic polygonal shape, zonal inclusions and optical behaviour. Accessory to the nepheline and leucite-bearing basalts are haüyne, nosean, melanite (black garnet), perowskite and melilite. (See Fig. 42.)

With regard to structure, the basalts are somewhat variable. In the common continental (*e.g.*, Sieben Gebirge) type the olivines and augites are porphyritic, while the felspar is mainly present in the microlitic ground-mass, in which there is usually also a small quantity of glassy base. In many British basalts, however, an ophitic or "intersertal"[1] structure prevails; and in these rocks a gradual passage to the ophitic dolerites can be traced. The andesites, into which the basalts also pass by every gradation, differ in the fact that in them the felspars are porphyritic and more abundant, while augite occurs in smaller and less frequent crystals, and olivine only as a rare accessory.

Basalt occurs in "flows" or beds of great extent and variable thickness, forming characteristic plateaux and terraced hills; also in dykes which, perhaps, represent, in some cases, the fissures through which the molten lava welled out.[2] The "bedded" basalt is slaggy and amygdaloidal on the outer surface. Internally it is characterized by a well-marked columnar structure, which has doubtless been developed by contraction during cooling. The columns are 3, 4, 6, and 8-sided, and are sometimes of great length and regularity, the long axes being perpendicular to the surfaces of cooling. A cross-jointing is sometimes superadded, producing a tabular structure. The spheroidal weathering of basalt is due to the presence of these intersecting joint-surfaces, along which permeating waters have access. Where basalt has been quickly cooled, by contact with cold rock, a thin layer or selvage of black opaque glass is invariably present. This basaltic glass is known as **tachylite.** It decomposes into a yellowish substance known as **palagonite.**

---

[1] Rosenbusch.

[2] In the "fissure-eruption" theory, which has not met with universal acceptation.

Basalt is very hard and tough, and constitutes an excellent material for paving and road-metalling.

DISTRIBUTION OF BASALTS AND MELAPHYRES IN THE BRITISH ISLES.

1. *England and Wales.*

The "Pebidian formation," which, according to Dr. Hicks, is of pre-Cambrian age, consists of basic lava. It is typically developed at St. Davids in Pembrokeshire. Contemporaneous volcanic rocks of basic composition occur in the neighbourhood of Rhobell Fawr, 5 or 6 miles N.N.E. of Dolgelly.

Basaltic lavas of Devonian age occur near Brent Tor (the denuded stump of a volcano) near Tavistock; also in the neighbourhood of Ashprington in Devonshire, and St. Minver in Cornwall.

Two beds of amygdaloidal basalt or melaphyre, locally termed "toadstone," occur in the Carboniferous Limestone of Derbyshire. They are well exposed in Miller's Dale, Tideswell Dale and near Matlock.

The N.-of-England dykes, though of basaltic appearance, mostly belong to an andesitic type.

Table Showing the Mutual Relations of the Basic Rocks.

	INTRUSIVE.		VOLCANIC.	
	Deep-seated (plutonic) masses.	*Dykes and intrusive sheets.*	*Fresh.*	*Altered.*
Gabbros	Diallage-gabbro	Dolerite (diabase)	Basalt and Tachylite	Melaphyre and Palagonite
	Hornblende-gabbro	Hornblende or mica -dolerite (diabase)	Hornblende or mica -basalt	
	Hypersthene-gabbro or Norite Pyroxene-granulite	Enstatite-dolerite (diabase)	Enstatite-basalt	
Nepheline-bearing basalts, etc.			Tephrite and Basanite	
			Nepheline Leucite Melilite -basalt.	

All these varieties with or without olivine.

2. *Scotland and Ireland.*

Porphyritic olivine-basalts occur abundantly in the Midland valley of Scotland: the Lion's Haunch, Dunsappie Loch, and Long Row, near Edinburgh; Hill of Dun at Bowling, 3 miles E. of Dumbarton; Douglas in Strathblane, 10 miles N.N.W. of Glasgow; and Stitchill, N. of Kelso, may be taken as examples.

In the Western Isles of Scotland and in the N.E. of Ireland ophitic olivine-basalts occur in horizontal beds or flows and dykes, displaying magnificent columnar structure, as at the famous Fingal's Cave in Staffa and at the Giant's Causeway on the coast of Antrim.

Many of the basalt-dykes in Arran, Mull, Raasay, etc., have narrow selvages of dark-coloured basaltic glass or tachylite.

Nepheline- and leucite-bearing basalts are not known to occur in the British Isles.

10. THE PYROXENITE[1] AND HORNBLENDITE[2] FAMILY.

The **pyroxenites** are plutonic or deep-seated rocks, composed of one or more varieties of pyroxene and having a holocrystalline and granular structure. The pyroxenes present are usually a green monoclinic variety (omphacite or diallage) and a strongly pleochroic rhombic variety (hypersthene). These rocks have received various names—diallagite, hypersthenite, websterite,[1] etc. As a rule, they contain neither felspar nor olivine; by the addition of the former, however, they pass into norites and gabbros, and by the addition of the latter into peridotites.

---

[1] Name introduced by Sterry Hunt, in 1862.

[2] Name introduced by J. D. Dana, in 1880.

The **hornblendites** are similar rocks, composed only of hornblende.

The beautiful rock known as **eclogite,** which is composed of emerald-green hornblende (smaragdite), grass-green augite (omphacite) and red garnet, belongs to this family.

This family is represented in the gneissose series of the Highlands of Scotland.

11. THE MAGMA-BASALT FAMILY.

The **magma-basalts** of Bořický are rocks consisting solely of ferro-magnesian minerals and iron-ore imbedded in an abundant glassy base. Augite of the

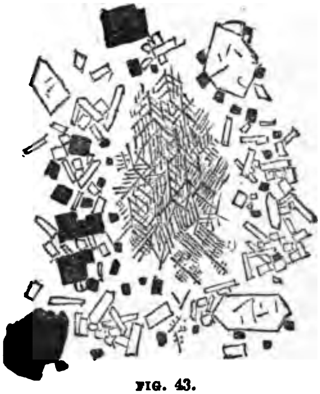

FIG. 43.

Magma-basalt, composed of crystals of Magnetite and Augite imbedded in a brown glassy base. In the centre is a patch of trichites. (*After Hatch.*)

---

[1] Name introduced by G. H. Williams, in 1890,

common brown type is the most abundant constituent; it occurs in prismatic crystals, giving 8-sided cross-sections, and in microlites. Iron-ore (magnetite) is always present, both in granules and trichites (see Fig. 43). Those rocks which, in addition to augite, contain olivine, are termed **limburgites**;[1] those without olivine, **augitites.**[2] According to Bořický, the magma-basalts contain 38·7 – 42·5% of SiO_2, 3·6 – 6·3% of alkalies, and 3 – 6·5% of water.

These rocks have not been described as occurring in the British Isles; but they have a widespread occurrence abroad: *e.g.*, Kaiserstuhl, Rhön and Vogelsberg in Germany; further, in Bohemia, in the Cape Verd Isles, at Kilimanjaro and in Madagascar.

12. THE PERIDOTITE AND SERPENTINE FAMILY.

The peridotites are ultra-basic rocks without felspar and composed mainly of olivine, the remaining constituents being one or more ferro-magnesian minerals or members of the iron-ore, spinel and garnet groups. The rocks are plutonic in their geological relations, *i.e.*, they are deep-seated intrusive rocks. They are especially remarkable for their basic character and high specific gravity: $SiO_2 = 39–45\%$; $Al_2O_3 = 0–6\%$; $FeO = 8–10\%$; $CaO = 0–2\%$; $MgO = 35–48\%$. Alkalies only in traces. Sp. G. 3·0–3·3.

The picrites, or felspar-bearing peridotites, which are appended below as a sub-group, have, as a rule, a somewhat lower specific gravity (2·8–2·96).

---

[1] Rosenbusch (1872).

[2] Dölter (1882).

The following combinations have been described:

Dunite[1] = olivine + chromite.

Wehrlite[2] = olivine + diallage.

Saxonite[3] or **Harzburgite.**[4] = olivine + rhombic pyroxene.

Lherzolite[5] = olivine + diallage + bronzite.

Cortlandite[6] = olivine + hornblende + hypersthene.

Eulysite[7] = olivine + augite + garnet.

Sub-group.

Picrite[8] and **palæopicrite**[9] = olivine + augite + a little felspar.

Hornblende-picrite[10] = olivine + hornblende + a little felspar.

By alteration under the influence of surface agencies the peridotites give rise to **serpentinous rocks**; and there is no doubt that a great number of serpentines have originated in this way. On the other hand, some serpentines have been shown to be derived from augitic rocks, such as gabbro, diabase, etc., and from hornblendic rocks, as in the case of the Rauenthal serpentine, described by Weigand. In each case the structure of the serpentine generally serves to indicate the nature of the mineral components of the rock from which it is derived. Thus serpentine derived from olivine is found to have a characteristic reticulated or "mesh" structure (see Figs. 24 and 25); that resulting from the alteration of augitic rocks (in the so-called **antigorite-serpentines**), a "netted"[1] or "bladed"[2] structure, due to the fact that the alteration proceeds along cleavage cracks which cross one another nearly at a right angle, thus producing a plexus of bladed forms, bearing a resemblance to network. Finally, the serpentine derived from hornblende-bearing rocks has a "lattice-structure," due to the alteration having taken place along cleavage cracks intersecting at an angle of 124°. Fragments of unaltered olivine, diallage and bastite are often found imbedded in serpentine, thus furnishing further proof of the mode of origin of these rocks. Again, their mode of occurrence, in dykes and bosses, leads to the same conclusion.

---

[1] Named after the Dun Mts. in New Zealand by Hochstetter in 1859.

[2] Von Kobell (1838).

[3] So named on account of their occurrence in Saxony, by Wadsworth, in 1884.

[4] Rosenbusch (1885).

[5] So named after Lake Lherz in the Pyrenees, by De la Méthérie.

[6] Name suggested by G. H. Williams.

[7] A. Erdmann (1849).

[8] Name given by Tschermak (in 1866) on account of the high percentage of magnesia (bitter-earth) in these rocks.

[9] Gümbel.

[10] Bonney (1881).

Serpentines are dull green and red, often mottled rocks. They are so soft that they can be easily scratched, or even cut with the pen-knife. Veins of fibrous chrysotile and steatite frequently traverse them. In some cases the serpentinous mineral is disseminated through limestone, as in the rocks known as "ophicalcite." Serpentine is used as an ornamental building-stone, also for the preparation of ornamental objects, *e.g.*, tobacco-jars, vases and other receptacles.

---

[1] Ger. *Gestrickte Structur.*

[2] Ger. *Balken Structur.*

DISTRIBUTION IN THE BRITISH ISLES.

Peridotites are not of very frequent occurrence in this country. Many of the varieties, however, are associated with the crystalline schists of the Highlands of Scotland (Sutherland). Picrites are associated with the gabbros and dolerites of the Western Isles of Scotland (Rum, N. of Skye, Shiant Isles). Picrite and hornblende-picrite occur in two localities near Edinburgh (Blackburn near Bathgate, and the island of Inchcolm); also in Wales and Anglesey (Penarfynydd, Penyrhiwan near Clynnog in the Lleyn peninsula, Caemawr and Pengorphwysfa in Anglesey); in the Lake District (Little Knott) and in Cornwall (Clicker Tor, Menheniot near Liskeard).

Serpentines are more abundant, occurring in many localities in Cornwall (Lizard district), Anglesey, Ayrshire, Aberdeenshire, Portsoy in Banffshire, and in the W. of Ireland (Connemara).

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